

# The Mistaken Extinction

## Chapter Four

### ***Enormous Eruptions and Disappearing Seaways: Evidence for the Volcanic Extinction Hypothesis***

Many well-documented pieces of geological evidence have been incorporated into developing the extinction scenario based on volcanism at the end of the Cretaceous. Recent revisions of this scenario have attempted to link volcanism with dramatic environmental changes that may have accompanied the retreating continental seaways. Over the last half of the 20th century, Earth processes such as volcanism, earthquakes, and the configuration of the oceans and continents have been tied to the mechanisms of plate tectonics. Plate tectonics has even assumed an important role in explaining how animals and plants came to be distributed the way they are around the planet. The emergence of plate tectonics as the predominant model for explaining changes on the Earth has revolutionized the way geologists and paleontologists view Earth and evolutionary history. So, before embarking on a detailed examination of the evidence for volcanism at the end of the Cretaceous, let us briefly introduce a simplified summary of how plate tectonics works.

#### *Summary of Earth Structure and Plate Tectonics*

As the Earth cooled after forming 4.5 billion years ago, it divided into several layers, including the core at the center, the mantle in the middle, and the crust at the surface (fig. 4.01). The rocky crust is the lightest layer, which essentially floats on the lower denser layers. Basically, the crust is composed of minerals containing relatively light elements, such as silicon, aluminum, and potassium. It is actually extremely thin, averaging about six miles (10 km) under the oceans and about 25 miles (about 40 km) under the continents. The mantle extends from the base of the crust to the core, in other words, down to about 1800 miles (2900 kilometers). The mantle is more dense than the crust because the minerals that make it up contain more heavy atoms. These include iron, magnesium, and even a little iridium (an element that will become very important to our discussion about possible K-T impacts). The core is even more dense than the mantle and is thought to be composed primarily of iron.

The mantle appears to circulate material in two layers of large convection cells--each cell moving material in a manner similar to that seen in a boiling pot of syrup (fig. 4.02)<sup>5</sup>. This convection, presumably fueled by the release of radioactive energy within the core, is thought to drive the motions of continents as they drift across the surface of the

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Earth as part of plate tectonic activity (fig. 4.03). Most of the movement within the mantle that drives the continents is thought to operate within the upper 400 miles (650 kilometers).

In essence, one might think of plate tectonics in terms of a gigantic recycling process for the Earth's crust (fig. 4.04). As material in the mantle heats at the base of the upper layer of convection cells, it rises toward the surface of the Earth. There, it erupts through fractures or rifts, spreading the plates of the crust apart (fig. 4.05). New crust is created along such spreading centers, and older crust is pushed off to the side. One prominent spreading center is represented by the Mid-Atlantic Ridge, which runs from above Iceland all the way down below the southern tips of Africa and South America. Where two plates collide, one dives beneath the other, and cooler mantle material descends back down toward the core. These areas are called subduction zones. One subduction zone borders the west coast of South America, where that continent overrides the floor of the Pacific Ocean. In essence, new crust is generally created at spreading centers, whereas old crust is melted and recycled at subduction zones. In addition to areas where crust is created and destroyed, plates can simply slide one another at the Earth's surface. The San Andreas Rift, which cuts across the western edge of California, is an example of such a boundary between plates. Earthquakes are generated when the rocky plates fracture and rupture as they move past one another or where molten bodies of rock move toward the surface. Now, how does the volcanism at the K-T boundary reflect the actions of plate tectonics?

### *The Deccan Traps and Other Cretaceous-Tertiary Volcanic Events*

As early as 1972, a geologist named Peter Vogt<sup>1</sup> of the Naval Research Laboratory in Washington, D. C. recognized that the extinctions at the end of the Age of Dinosaurs coincided with a tremendous increase in volcanic activity throughout the world. Huge volumes of basaltic lava erupted and flooded over large areas on the floor of the Indian Ocean and India itself, as it drifted northward because of plate tectonics toward a collision with Asia. Basalt is the dark volcanic rock generated by Hawaiian volcanoes in the Pacific.

Vogt is now said to favor the impact hypothesis, but others have picked up on his original idea. Research relating these massive eruptions to dinosaur extinction has been spearheaded by Charles Officer and Charles Drake of Dartmouth College in the United States, as well as by Vincent Courtillot at the Institute of Physics of the Earth in France<sup>2-5</sup>.

Although about 15% of the Indian eruptions may have been catastrophically violent, most are not thought to have been terribly energetic. Nonetheless, the resulting lava flows document one of the

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largest single volcanic events in the history of the Earth. The scale of the eruptions is dumbfounding even to geologists. Over a 500,000-year-interval between 66 million years ago and 65 million years ago, almost 480,000 cubic miles (2,000,000 cu km) of molten lava flowed out of cracks and fissures in the Earth's crust near the present-day Indian coast and flooded hundreds of miles inland<sup>5-8</sup>. As a result of the plate tectonic movements that have occurred since the end of the Age of Dinosaurs, some of these lava flows are now exposed along the western coast of India, while others form the seabed of the Indian Ocean around the present-day Seychelles Islands.

These flows make up a geologic feature called the Deccan Traps (fig. 4.06). The name carries a descriptive significance: In Sanskrit, "Deccan" means "southern," which is appropriate because the flows are now situated along the southwest coast of India. In Dutch, "trap" means "staircase," which refers to the steplike pattern that typifies the erosional surface of the flows piled one on top of the other. At some localities, the sequence of flows is over 8,200 feet (2,400 meters) thick<sup>5</sup>. This is more than 25% of the height of Mount Everest, which began to rise later as India slammed into Asia between 40 and 60 million years ago. The lava may have originally covered an area larger than California (fig. 4.07)<sup>10</sup>. On average, it is estimated that the flows erupted at a rate of between one-half and two cubic miles (about two to eight cubic kilometers) annually<sup>9</sup>. Individual lava flows in the Deccan Traps average between 32 and 164 feet thick (about 10 to 50 meters), although the most extensive ones attained a thickness of almost 500 feet (150 meters).

The question of how long individual eruptions lasted is controversial<sup>10</sup>. Volcanologists including Donald Swanson of the U. S. Geological Survey originally interpreted the geologic evidence to suggest that individual flows occurred over a matter of a few days. More recently, however, Stephen Self of the University of Hawaii and his colleagues have argued that the evidence suggests that the individual eruptions may have lasted a year or longer.

Much scientific interest and debate has surrounded the question of how such monumental volcanic events were generated. Recent research has provided strong evidence that the Deccan Traps represent the end product of a slowly ascending, gigantic plume of molten rock or magma from deep within the Earth. This plume may have originated as deep as the boundary between the core and the mantle<sup>5,7-10</sup>.

As early as the 1960s and 1970s geologists and geophysicists, such as W. Jason Morgan of Princeton University, proposed that flood basalts represented plumes of magma that arose from within the Earth's mantle<sup>10</sup>. The reason that this was suspected was because the chemical

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composition of the flood basalt that makes up the flows is similar to the composition of the material that geologists believe makes up the mantle. However, the evidence for the deep origins of this magma was not strong.

The scenario involving the origin of flood basalts goes like this. A tremendous amount of heat is released from the mantle through volcanism at spreading centers. In fact, this is generally how heat is released from inside the Earth. About one tenth of the heat escaping from the mantle, however, arises from deep-seated, thin "roots" that extend all the way down to the boundary between the mantle and the core ( see fig. 4.02)<sup>9</sup>. Because these thin plumes are warmer than the surrounding mantle material, they rise until they reach the base of the crust. As they rise, a spherical head forms at the top of the plume as it forces its way up through the cooler surrounding material of the mantle. As the plume reaches the base of the crust, it spreads out, creating a mushroom-shaped body of material. The force of the rising plume with its mushroom-shaped head lifts a large area of the overlying crust, making it thinner and fracturing it as it is lifted<sup>5,8,9</sup>. Because the pressures at these shallower depths within the Earth are much less than those near the core, the plume decompresses and the rock partially melts. As it nears the surface of the crust, the volatile gases dissolved in the magma are released, somewhat like the effect generated by opening a bottle of soda or champagne. The upwelling lava then spews out from the fractures in the uplifted crust. The place where the lava erupts on the surface is called a hot spot. Once erupted, the lava floods downhill over the Earth's surface to form new crust.

Some geologists, including Vincent Courtillot, have argued that the record of magnetic reversals at the end of the Cretaceous also conforms to the scenario outlined above<sup>5</sup>. That argument proceeds as follows: The molten iron and nickel in the Earth's outer core is thought to circulate slowly by means of convection at a rate of about 6 miles (10 kilometers) per year. In turn, these movements are thought by many earth scientists to produce the Earth's magnetic field. Unstable conditions that occasionally arise at the boundary between the mantle and core are believed to cause the reversals of the Earth's magnetic field, a phenomenon mentioned in Chapter 2. These unstable boundary conditions apparently result from the release of heat from the core into the mantle. As heat generated by radioactive decay radiates out of the core, the lower layer of the mantle heats up and becomes less dense. From time to time, this lowest layer of the mantle, called the "D-layer", becomes so thick and light that instability results and large volumes of material are released to rise as plumes of magma. As the D-layer grows thicker, reversals in the Earth's magnetic field are few and far between,

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such as the long interval of normal polarity that existed between about 120 million years ago and 80 million years ago (fig. 4.08). At the end of that period, which is called "The Cretaceous Long Normal," the D-layer apparently became unstable and broke up releasing enormous plumes of magma rising within the mantle. As the exchange of heat from the core to the mantle increased, reversals in the Earth's magnetic field resumed on a more frequent basis. Presumably it took millions of years for the largest of these plumes to reach the surface of the Earth, at which time it resulted in the hot spot eruptions that formed the Deccan Traps and the undersea plateau around the Seychelles Islands.

Most of the lava flows of the Deccan Traps erupted over a period of about a half a million years between 66 and 65 million years ago in a series of massive pulses. According to Asish Basu from the University of Rochester and his colleagues, the earliest eruptions began about 68.5 million years ago, and the latest volcanic activity ended about 64.9 million years ago<sup>6,7</sup>. However, activity near the original point of eruptions continues even today in the form of a volcano called Piton de la Fournaise on Reunion Island in the Indian Ocean. In essence, the plume that reached the surface of the Earth's crust about 66 million years ago has created a hot spot for volcanic activity ever since.

The Deccan Traps, although the largest-known volcanic event at the end of the Age of Dinosaurs, was by no means the only one<sup>11</sup>. More volcanism is recorded in deposits at the bottom of the South Atlantic Ocean near Antarctica. The volcanic rocks of K-T age form part of the Walvis Ridge that ends at the volcanic island of Tristan da Cunha. In all, the ridge comprises a largely submerged mountain range that resulted from the eruption of another plume of magma that began before the end of the Cretaceous but remained active during the K-T transition (fig. 4.09). F. L. Sutherland of the Australian Museum identified as many as eight other centers of hot-spot volcanism in the southern Atlantic, as well as in southern Africa and eastern South America, which may have been active during the Cretaceous-Tertiary (K-T) transition. Precise radioisotopic dating has yet to pin down the ages of these eruptions very precisely, however.

More evidence for K-T volcanism is found in another part of Africa<sup>11</sup>. Crossing the west coast of central Africa is a linear deposit of basalt that began to erupt about 65 million years ago. It is called the Cameroon line, and it appears to be linked to nearby faulting that served to separate Africa from South America. These eruptions are thought to have been generated by another plume from the mantle.

Further north, the hot spot now associated with the volcanic activity in Iceland may have originated under Greenland and helped initiate the

plate tectonic separation of Europe and North America from Greenland<sup>11</sup>. The latest recalculations of the age of this activity suggests that the volcanism began near the K-T transition, although much of the volcanism occurred later in the the Tertiary.

In the central Pacific lies a familiar string of islands long recognized to have been created by hot spot volcanism--the Hawaiian Islands. The oldest major eruptions that formed the Hawaiian-Emperor chain appear to have begun about 65 million years ago<sup>11</sup>. However, most of the islands are younger in age.

Off the north east coast of Australia, an intensive episode of hot-spot volcanism is though to have begun about 65 million years ago at rifts that began to open up the Coral and North Tasman seafloors. Other volcanic provinces associated with plate tectonic activity in Australia during the K-T transition include the Bass Basin and the main segment of the Tasman rift<sup>11</sup>.

Not all geologists agree that these volcanic plumes come from deep within the Earth as proponents of volcanic extinction scenarios suggest. Don Anderson, a geophysicist at the California Institute of Technology, argues that flood basalts arise at depths of no more than 250 miles<sup>10</sup>. But what evidence is there to suggest that they originate from near the core-mantle boundary? Much of the work is based on analyzing different forms, or isotopes, of the atom helium<sup>7,10,12</sup>. This is a fascinating scientific detective story whose roots extend all the way back to the origin of the universe at the Big Bang about 15 billion years ago.

In some ways this apparent tie between the most momentous volcanic events on Earth and the most momentous event in the universe seems quite fitting. Cosmological models suggest that a particular kind of helium atom, termed helium-3, was created within the first two minutes after the Big Bang initiated our universe. Along with hydrogen, which was created at the same time, helium-3 comprised one of the two basic components from which galaxies and stars were eventually formed, including our solar system with its sun and planets. Helium-3 was also incorporated into the Earth as it grew, or accreted, about 4.5 billion years ago by gravitationally attracting smaller objects, such as comets and asteroids. However, helium is not common in the rocks of the Earth's crust because it is so light, as evidenced by helium balloons which tend to float annoyingly away as any child can tell you. Similarly, helium escapes from the pores in rocks as they are eroded and broken during the process of weathering and remelting as igneous rocks are reconstituted into sedimentary and metamorphic rocks.

In the late 1960s and early 1970s, small traces of helium-3 were found in emissions from spreading centers under the ocean<sup>10</sup>. It was concluded that these traces were derived from material that had risen from within the mantle where it had been trapped since the early stages of the Earth's formation. In addition, relatively large amounts of helium-3 were discovered to be coming out of hot spot volcanoes such as the one now located at Reunion Island, which represents the remnant of the source for the Deccan Traps. In the late 1980s, this led geochemist Asish Basu of the University of Rochester and his colleagues to carefully analyze the atomic composition of some of the earliest-known rocks erupted in the Deccan Traps. Amazingly, in some relatively unweathered samples of these rocks, relatively large traces of helium-3 were found to have been preserved in microscopic bubbles that formed inside the rock as it cooled and solidified before it could reach the surface and be released into the atmosphere. To Basu and many other geologists this represents strong evidence that the plume responsible for the Deccan eruptions originated at the base of the mantle near its boundary with the core.

Robert White and Dan McKenzie at the University of Cambridge have suggested that the rising plumes of magma that fed these huge volcanic eruptions served to lift the continents up and assist the process of continental breakup, or rifting<sup>8</sup>. According to the late Anthony Hallam of the University of Birmingham, such uplift may have had a role in causing the long-recognized retreat of shallow continental seaways back into the major ocean basins at the end of the Cretaceous<sup>13</sup>. To support the proposal that these plumes could have uplifted the continents and eventually caused the retreat of the shallow seaways, proponents like Hallam have noted that topographic high spots on the crust are associated with areas where plumes are rising to the surface today, such as around the Hawaiian Islands. This idea has yet to be thoroughly tested. It should be noted, however, that in some areas where seaways retreated, such as North Africa and Europe, no plumes appear to have been actively generating eruptions during the K-T transition. In addition, some of the K-T volcanic activity, including that at the Walvis Ridge and the part of the Deccan eruptions now located near the Seychelles Islands, occurred on the seafloor. Such seafloor eruptions would seem to have raised rather than lowered sealevels.

Finally, numerous layers of siltstone and mudstone, rich in altered volcanic ash derived from eruptions associated with the uplift of the ancestral Rocky Mountains, are preserved in ancient floodplain sediments now exposed in Wyoming, Montana, North Dakota, South Dakota and Alberta. These were deposited by rivers along the shoreline of the late Cretaceous seaway that bisected North America (fig. 4.10). Most beds from: *The Mistaken Extinction – Dinosaur Evolution and the Origin of Birds*, by Lowell Dingus and Timothy Rowe, 1998. W. H. Freeman, New York. Reproduced here for UT Geo 302d, by permission of authors.

are not pure volcanic ash. They have been washed around with other sediments on the floodplain adjacent to the seaway. Nonetheless, a good deal of this material was probably erupted between 70 million and 65 million years ago.

Personally, this is one of our favorite field areas in the world. We have been making annual pilgrimages to study the rocks and fossils exposed in these rugged badlands ever since we became students at Berkeley. The ash-rich rocks are noted for the "popcorn"-like texture found on the surface of these exposures. After the volcanic ash weathers to clay, it can expand by absorbing large quantities of rain water, kind of like a dry compressed sponge does when it is placed in water. This expansion creates the popcorn-like surface texture. If you're trying to walk or drive across these exposures when they're wet, forget it. The rain transforms them right back into a Cretaceous swamp, and you'll either get stuck or fall flat on your behind before you can blink.

These beds form the rock units called the Hell Creek and Lance Formations, and they are world famous for the fossils that they contain. From these exposures, paleontologists and public alike got their first glimpses of the three-horned dinosaur, *Triceratops*, and the "king" of the dinosaurs, *Tyrannosaurus*. As we shall see in Chapter 7, fossils from these rock units provide the most complete picture of biologic change on the continents during the K-T transition known from anywhere in the world.

Working with our former classmate, Carl Swisher of the Berkeley Geochronology Center, we collected samples from several layers of altered volcanic ash near the K-T boundary in this region. Previously, age estimates for the boundary had ranged between 64 and 66 million years ago. Based on our radioisotopic dating of minerals in these layers, the last dinosaurs and Cretaceous plants lived in this area slightly before 65.01 million  $\pm$  30,000 years ago<sup>19</sup>. Our date coincides with the final phases of Deccan volcanism, which ended at 64.96 million  $\pm$  110,000 years ago<sup>7</sup>. This suggests, but certainly does not prove, that the environmental effects of the Deccan eruptions could have been linked to the K-T extinctions. What would the environmental effects of the eruptions have been?

### *Environmental Effects Associated With the Eruptions*

As mentioned earlier, these shallow continental seaways helped maintain the equable, subtropical environments in which the dinosaurs thrived. However, over a period of about 100,000 years at the end of the Cretaceous, as the seas rapidly retreated, climates became more extreme.

Vincent Courtillot, Charles Officer, Charles Drake, and Anthony Hallam argue that all this K-T volcanism could have spewed tremendous

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quantities of dust and sulfate aerosols into the atmosphere, generating both long- and short-term effects<sup>4,5</sup>. Shortly after major eruptions, the emissions of dust, sulfur dioxide and other gases could have caused acid rain, acidic layers of water near the surface of the oceans, a cooling of air temperatures, depletion of the Earth's ozone layer, and possibly darkness.

The estimated amounts of pollutants that would have been injected into the atmosphere by the sequence of eruptions that formed the Deccan Traps are truly staggering<sup>5</sup>: up to 30 trillion tons (27 trillion tonnes) of carbon dioxide, six trillion tons (5.4 trillion tonnes) of sulfur, and 60 billion tons (54 billion tonnes) of chlorine and fluorine molecules. An initial cooling of the global climate of between five to nine degrees F (three to five degrees C) would be triggered by the volcanic ash and sulfur emitted by a single Deccan eruption generating 250 cu miles of lava (1000 cu km). Sunlight to the Earth's surface would be cut substantially, inhibiting photosynthesis. Emissions of sulfur dioxide would turn the surface layers of the ocean into acidic baths, killing the microscopic organisms that normally process carbon dioxide in the atmosphere. Over the long-term, the carbon dioxide rose to levels eight times that found in today's atmosphere, increasing the average global temperature as much as nine degrees F (five degrees C) as the result of the greenhouse effect. As with earlier hypotheses involving the retreat of seaways, proponents of the volcanic scenario argue that the dinosaurs could not tolerate these toxic environmental conditions or climatic extremes and perished in the face of prolonged environmental stress.

However, critics respond: Why didn't the freezing winters and torrid summers extinguish turtles, snakes, lizards, and crocodiles-- animals that are at the mercy of the climate to maintain a livable body temperature? They were all around at that time. It's hard to see why the physiology of those reptiles wasn't affected, whereas that of the dinosaurs was decimated. In addition, this was not the first time that large volcanic events had occurred during the Age of Dinosaurs. Why did dinosaurs survive earlier ones, but not this one?

#### *Coincidence Between Other Large Volcanic Events and Mass Extinctions*

The K-T extinction episode is not the only mass extinction in evolutionary history that appears to be associated with an enormous volcanic event that resulted from plumes within the mantle<sup>7,14,15</sup>. The largest mass extinction in history occurred about 250 million years ago at the end of the Paleozoic Era and the beginning of the Mesozoic Era (fig. 4.11). This episode is believed to have extinguished as many as 95% of all the Earth's species living at that time<sup>5,9,16,17</sup>. Ironically, it was the

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extinctions of early relatives of mammals, the dominant land animals of their time, that most paleontologists believe was responsible for creating the empty ecological niches which were filled by the dinosaurs after their origin about 230-240 million years ago (fig. 4.12).

The most enormous outpouring of continental flood basalts in the history of the Earth also occurred at that time. The Siberian Traps in Russia document that event. The amount of lava erupted to form the Siberian traps was truly mind-boggling--up to 800,000 cubic miles (3 million cubic kilometers). If the lava had spread itself evenly across the entire surface of the Earth, it would have left a layer of basalt up to ten feet thick<sup>10</sup>.

Paul Renne of the Berkeley Geochronology Center, along with Asish Basu and their colleagues, have established that the volcanism that generated the Siberian Traps began around 253 million years ago. However, the main pulse of eruptions began about  $250.0 \pm 0.3$  million years ago<sup>12,18</sup>. The time of the extinctions was  $250.0 \pm 0.2$  million years ago. Consequently, within our ability to tell time at the end of the Paleozoic, the dates are indistinguishable, suggesting that the eruptions could have caused the extinctions. Renne and his colleagues argue that the Siberian eruptions could have produced enough sulfur-based aerosols to cause acid rain and rapidly cool the global climate, generating polar ice caps. Ice cap formation could have initially led to a retreat of the seas, aided by the uplift generated by the enormous rising plume. Such environmental disruption is blamed for the massive extinctions. To date, no compelling evidence for an extraterrestrial impact at the Permian-Triassic boundary is known.

Although all the environmental effects associated with these large volcanic events are possible and may have caused the K-T extinction of many kinds of dinosaurs, this plethora of potential "killing mechanisms" presents us with a difficult problem. As the number of "killing mechanisms" increases and the scenario becomes more complex, it becomes even harder to test and pinpoint which mechanism or combination of mechanisms resulted in the extinction of particular groups of animals or plants. A wealth of ways to die doesn't necessarily lead to a clearer picture of why. Besides, with all these potential ways to become extinct, why were the plants and animals that survived not affected? The reason for their physiological tolerance is difficult to understand. In addition, not all large continental episodes of basalt floods appear to be associated with large extinction events. One is the Columbia River Basalts in Oregon, which erupted about 16 million years ago<sup>10</sup>. Why aren't there extinctions associated with that event? Was it too small?

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These problems and questions leave many scientists perplexed. The volcanic scenario for extinction just doesn't seem to explain all the available evidence in the rock and fossil record. Thus, in the late 1970s and early 1980s a new hypothesis was proposed while we were graduate students at Berkeley. This revolutionary proposal linked the K-T extinctions to the impact of an asteroid or comet. But, how strong is the evidence documenting that K-T impact? The next two chapters will examine the geologic record to evaluate that question.

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## Captions for figures in Chapter 4

### fig. 4.01

The interior of the Earth is divided into several different layers. Both the continents and ocean floors are parts or plates of the crust formed by the lithosphere. A ductile layer called the asthenosphere, on which the plates float, lies below the lithosphere and forms the lower part of the crust and upper part of the mantle. The lower part of the mantle lies above the core. The depth of each layer is provided. (from Press and Seiver, 1978, *Earth*, fig. 1-10)

### fig. 4.02

This cross section of the Earth show how plumes of hot light magma rise from near the boundary between the mantle and the core to erupt at the Earth's surface. One such momentous eruption was responsible for the thick pile of lava flows that form the Deccan Traps. (from Coffin and Oldham, October 1993, *Scientific American*, p. 46)

### fig. 4.03

The plates of the Earth's crust, which form the continents and ocean floors, move across the surface of the Earth as the result of plate tectonic forces that are generated in the mantle by convection. Plates move apart at spreading centers, such as the mid-Atlantic ridge. At subduction zones, like the oceanic trench off the west coast of South America, one plate dives down under the adjacent one and melts. In this way, the crust of the Earth is continually being recycled. (from Moores and Twist, 1995, *Tectonics*, p. 6)

### fig. 4.04

This map of the Earth's surface show the present-day location of the major oceanic and continental plates. (from Moores and Twist, 1995, *Tectonics*, p. 7)

### fig. 4.05

A cross section through the upper layers of the Earth illustrates how plates move apart at spreading centers and how one dives under another at subduction zones. Volcanic activity and earthquakes are most common at spreading centers and subduction zones. (from Press and Seiver, 1978, *Earth*, p. 461)

### fig. 4.06

This rugged landscape shows some typical exposures of volcanic rock that outcrop as part of the Deccan Traps in India. The steplike

from: *The Mistaken Extinction – Dinosaur Evolution and the Origin of Birds*, by Lowell Dingus and Timothy Rowe, 1998. W. H. Freeman, New York. Reproduced here for UT Geo 302d, by permission of authors.

nature of the exposures is created by erosion of the individual lava flows, which are piled one on top of the other. (from White and McKenzie, July 1989, Scientific American, p.63)

fig. 4.07

These two maps contrast the lava flows of the Deccan Traps as they existed 65 million years ago (a) and as they exist today (b). The splitting of the flows occurred as India drifted toward Asia as the result of plate tectonic action. (from White and McKenzie, July 1989, Scientific American, p. 68)

fig. 4.08

Driven by heat generated through radioactivity, convection currents in the mantle of the Earth carry the plates of the Earth's crust on their drifting paths. The D-layer is found at the base of the mantle, just above the core. (from Courtillot, October 1990, p. 92)

fig. 4.09

This surface map of the Earth's continents and ocean basins shows areas of major volcanic activity at the time of the K/T transition: DT=Deccan Traps, TC=Tristan da Cunha, CL=Cameroon Line, GR=Greenland Hot Spot, HE=Hawaii-Emperor Hot Spot, CS=Coral Sea Hot Spot, HC=Hell Creek Volcanic Sediments. (adapted from Sutherland, 1988, Journal and Proceedings of the Royal Society, New South Wales, v.121, p. 141)

fig. 4.10

Exposures of the Hell Creek Formation in east-central Montana contain over two hundred feet of bentonitic siltstones, mudstones, and sandstones. Many of these layers were derived from volcanic ash erupted out of the ancestral Rocky Mountains, which were rising about 100 miles to the west. (slide by L. Dingus)

fig. 4. 11

Two maps from the Siberian platform in Russia depict the location of the Siberian Traps, which represent the largest known volcanic event in the history of the Earth. It happened at the end of the Paleozoic Era about 250 million years ago. (from Renne and Basu, 1991, Science, v. 253, p. 176)

fig. 4.12

The skeleton of *Moschops capensis* illustrates one of the larger early relatives of mammals that lived near the end of the Paleozoic Era. The lineage of these early relatives of mammals was severely affected by the extinction event at the end of the Paleozoic, an event which killed off as many as 95% of the species living on the Earth at that time. (from Dingus, et al., 1995, The Dinosaur Halls, AMNH, p.12)