ing the dominant members of ecological communities and enabling life to move off in new and unexpected directions.

Before anyone rushes out to proclaim that mass extinction is a good idea, remember how long the recovery lasted. The 5 million years after the end-Permian mass extinction were a pretty lousy time to be alive (even for snails), and the diversity of life in the seas did not begin to approach preextinction levels for tens of millions of years. A long time to wait.

CHAPTER 2

A Cacophony of Causes

As Europeans began exploring the world in the seventeenth century they came upon the ruins of great civilizations: the pyramids and Great Sphinx in Egypt, Ur in Mesopotamia, and eventually the New World Mayan ruins of Copan and Tikal, and Machu Pichu of the Inka. These complex civilizations and other vanished centers like Mesa Verde of the *Ancient Puebloans* in the American Southwest or the Moundbuilders of the Mississippi Valley continue to fascinate archeologists and the general public. Something deep within us (fear, perhaps?) renders stories of decline far more attractive than the long, preceding periods of success. Explanations for the collapse of such societies run the gamut from warfare and political intrigue to plagues, environmental degradation and other disasters. Despite the rich historical and archeological records of these societies, discriminating between competing hypotheses is frustrating. Some archeologists have championed a single cause upending a society, while others have adopted a more nuanced approach, constructing intricate webs of interacting causes.

Similarly, paleontologists look at mass extinctions as extraordinary events demanding amazing and wondrous causes. But as with more recent human events, there are often so many competing geological, climatic, and chemical events that establishing which represents the cause of the extinction and which the effect is a real challenge. This chapter considers the myriad different causes that have been proposed for the Permian-Triassic mass extinction, from volcanism to climate change and low oxygen in ocean waters. Ideally, from each hypothesis should flow testable predictions. If an extraterrestrial impact occurred, for example, the resulting mass extinction must have been very rapid, nearly simultaneous around the world, and we should be able to find some evidence of the impact (unless it was one of those stealth impacts of which a few commentators are so enamored). Some of my favorite hypotheses, so aesthetically pleasing that they really ought to be true, are either clearly wrong or cannot even be tested. In understanding the reasons for the collapse of ancient civilizations a comparative approach is useful for providing a sense of the range of plausible explanations. If there is no evidence that hurricanes destroyed any other tropical civilization, they are an unlikely explanation for the fall of the Maya. So before setting off through a cacophony of competing hypotheses for the Permian mass extinction, I begin with a quick tour through other biodiversity crises and their causes.

. . .

The Permian was "discovered" by Sir Roderick Impy Murchison in 1841 in the rocks of the Ural Mountains of Russia. Far from impy, Murchison was the imperious director of the British Geological Survey and a powerful presence in mid-nineteenth-century European geology. British colonialism knew no bounds, and Murchison was keenly interested in proselytizing for the "right" sort of geology where one of the principal goals was delineating rocks encompassing units of geologic time. He had previously recognized other time units, including the Silurian, a distinctive suite of rocks in the Welsh borderlands that he named after the ancient tribe that once inhabited the region. Gradually these distinctive packages of rock and their characteristic fossils were assigned names, often after the ancient tribes where the interval was first recognized. Murchison visited Russia in the 1840s at the invitation of the czar and identified a sequence of rocks and fossils in the Ural Mountains that were clearly different from the older Carboniferous rocks of Britain, or the younger Triassic rocks of Europe. These became the Permian, named after an ancient kingdom in the area that also gave its name to the city of Perm. (I wonder how many Texans knew, during the height of the Cold War, that Permian High School in Midland traced its name to the Russian heartland.) The geologist von Alberti had described a series of rocks in the Alps as the Triassic, and it soon became evident that these lay just above Murchison's Permian. Through this process of identifying packages of rocks with distinctive fossils, by the late 1800s European geologists established the relative order of different geologic units into the geologic timescale. Today we know the Permian stretches from about 298 million years ago to 251.6 million years ago, but neither Murchison nor von Alberti had any sense of this.

Murchison and von Alberti's correlations between Russia, the Alps, and England, indeed all the correlations made by geologists across Europe during the middle 1800s, relied on fossils. Following a century or so of confusion geologists had recognized that similar rocks were produced in similar environments, sandstones by rivers and shorelines, shales in offshore basins, carbonates near reefs, and so on. There was no reason to believe that two sandstones, even two red sandstones, were of the same age. With the realization that particular kinds of fossils occurred only during a narrow span of time came the discovery of correlation: the use of these fossils as a basis to infer that the rocks in which they were found were formed at the same time. From this was born the ability to map geologic units in space, to order rocks in time, and ultimately to develop a sense of the history of the earth. If fossil A is always found beneath fossil B in England, and B always lies beneath fossil C in France, then the rocks containing A must be older than those containing C. Through a series of such hypotheses, tested and retested against reports from the field, the geological time scale was established.

The geologic time scale was largely based on the rocks and fossils uncovered in Britain and Europe, but because the extinctions reflect global events it would look much the same had it developed in China, Canada, or Peru. There are a few exceptions. Nothing much happened during the Silurian and it differs little from the Lower Devonian, so it is hard to consider the creation of the Silurian Period as anything but an unfortunate mistake. Similarly, the division between the Carboniferous and Permian is so obscure in the United States that American geologists argued over the dividing line into the 1960s. Nonetheless, the fossils of the Cambrian to Permian share far more in common than they do with those of the Triassic through Cretaceous, or with the post-Cretaceous.

John Phillips was the first geologist to recognize the implications of this pattern. In 1840 Phillips divided the fossil record into the Paleozoic, Mesozoic, and Cenozoic eras. The fossils of each era were so distinct—the brachiopods, crinoids, and bryozoans of the Paleozoic; some bivalves of the Mesozoic; and the gastropods, crabs, and other bivalves of the Cenozoic—that Phillips was convinced each represented a separate creation of life. This was a perfectly logical assumption in Phillips's world. Letters between Phillips and Darwin make it clear that he never adjusted to Darwin's theory of evolution. In 1860 he drew the first illustration of the diversity of life through time (figure 2.1). The boundaries between the eras, and between many periods, are defined by major turnovers in the dominant fossils. In other words, by mass extinctions. Phillips first considered the relative durations of the different periods, but along with other geologists and physicists in the mid-1800s, he was soon caught up with trying to estimate how much time in years (what geologists call absolute time) was occupied by different periods. He focused on the amount of time required to deposit and erode sediments, and his 1860 estimates of the relative durations of the three eras are remarkably close to our present understanding based on precise radiometric dating. In fact, Phillips's estimate of the absolute age in years of the Cretaceous was far more accurate than Darwin's.

Animal fossils only extend through the last 550 million years of the earth's 4.6 billion year history. During this span, paleontologists have identified six great mass extinctions[1] (figure 2.2), although two of these events may be more artificial than real.

We will begin by working backwards in time from the best-known mass extinction, the end-Cretaceous event 65 million years ago when the environmental effects of the impact of a large, extraterrestrial object in the Yucatan Peninsula of Mexico wiped out the dinosaurs. In the Late Cretaceous dinosaurs dominated the land, and after some 150 million years of evolution had diversified widely. Mammals were widespread, but the great diversification of modern placental mammals would not occur until after the extinction. Many different kinds of flowering plants had appeared

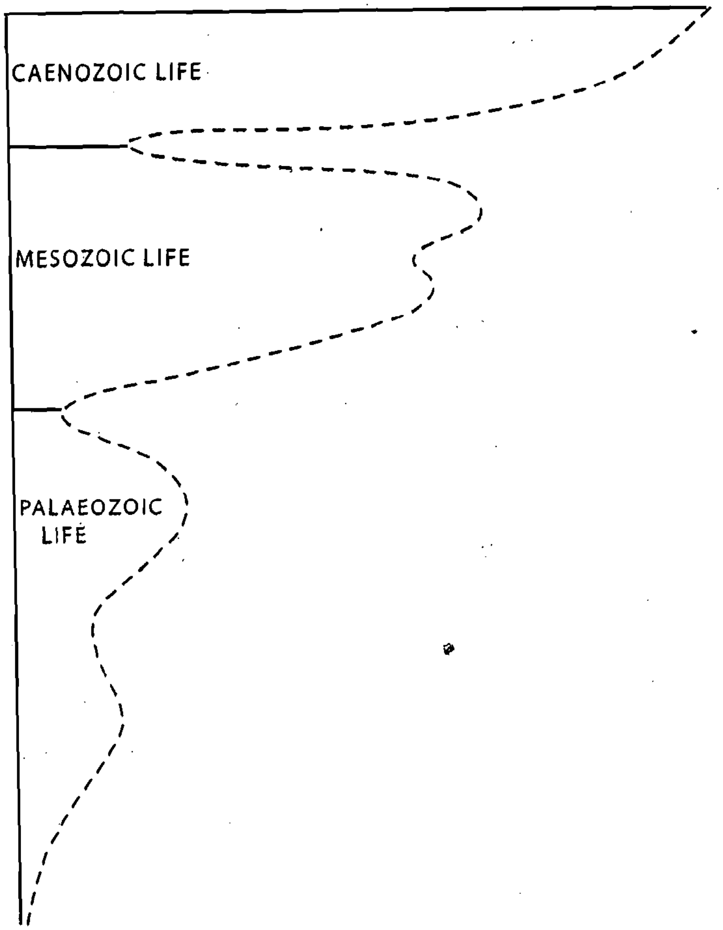

Figure 2.1 The first figure depicting the diversity of life through the Phanerozoic, published by John Phillips in 1860. Note the major drops in diversity corresponding to the end-Permian and end-Cretaceous mass extinctions. Phillips did not concern himself with the extinctions as such, and it would be almost a century before paleontologists began to explore their causes.

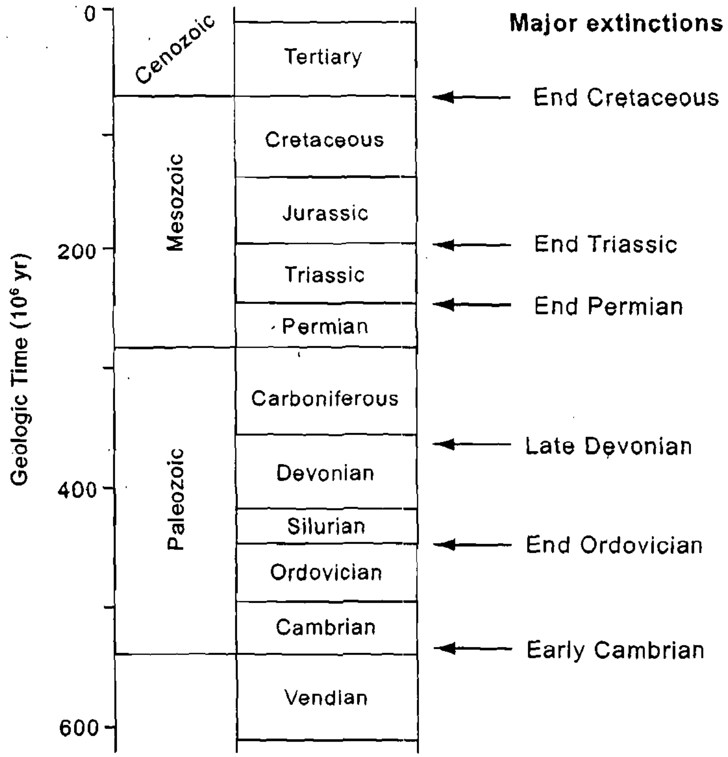

Figure 2.2 The major mass extinctions of the past 600 million years.

in only a few tens of millions of years of the Late Cretaceous. Ocean life bore many relationships to modern ecosystems, with the critical exceptions that corals were relatively insignificant and Late Cretaceous reefs were built by massive, conical bivalves known as rudists, and the coiled ammonite cephalopods flourished as major predators. The extinction eliminated some 47% of marine genera and 16% of families, including several microfossil groups, some bivalves, and the ammonites. Mososaurs and other marine reptiles became extinct too. Plants suffered considerable turnover, with one analysis from the northern Rocky Mountains suggesting a 79% extinction. So much more is known about this extinction than any of the other crises that it is worth considering it in greater detail.

The suggestion that a massive asteroid hitting the Yucatan Peninsula was the trigger has revolutionized geology. For over a century geologists had banished any discussion of catastrophist or extraterrestrial influences on geology, and particularly on the history of life. When in 1980, the father and son pair of Louis and Walter Alvarez and their colleagues from the University of California, Berkeley, linked the end-Cretaceous mass extinction to an extraterrestrial impact, they were met with skepticism and even scorn by most paleontologists, and for fairly good reasons. Geological training since the mid-1800s had emphasized the primacy of slow, gradual, processes and rejected catastrophic explanations, particularly extraterrestrial ones. Geologists were not blind to the existence of meteorite impacts—many had been identified during the geological fieldwork spurred by the Apollo program—and catastrophist theories were proposed from time to time. But speculations connecting impacts and major events in the history of life were either ignored or discounted. Geologists knew (or thought they knew) that was not the way the world worked. Although some physicists viewed this as simple obstinacy, in 1980 the pattern of extinction appeared gradual. Paleontologists reasonably expected that a catastrophic mass extinction should produce an abrupt and catastrophic disappearance of species in the fossil record.

The critical feature of the Alvarez impact hypothesis was the discovery of a thirty-fold increase in concentration of the element iridium at the Cretaceous-Tertiary boundary at Gubbio, Italy, and at other sites. Earlier work had suggested that iridium in sedimentary rocks came from the constant rain of micrometeorites. Louis Alvarez suggested to his son Walter, a professor of geology at Berkeley, that the changing abundance of iridium in marine sediments might be a useful index for changes in sedimentation rates. Assuming the influx of extraterrestrial debris was constant, if the rate of sediment deposition slowed, then the abundance of iridium in a given thickness of sediment should increase (since that layer of rock would be sampling the extraterrestrial debris deposited over a longer span of time). When Walter Alvarez and his colleagues applied this to the Cretaceous-Tertiary section at Gubbio, they found an incredible spike in iridium concentration right at the boundary. Moreover, they uncovered a similar pattern at two other sites, in Denmark and New Zealand, indicating that whatever caused the iridium spike, the pattern seemed to be global. They realized that the most plausible explanation was not a change in the rate at which the sediments had been preserved; the increase in iridium was too great. Instead they proposed that the impact of a meteorite or comet ended the reign of the dinosaurs.[2]

Whether it was a meteorite or a comet, the object that struck the Yucatan Peninsula was some 10–15 kilometers in diameter. Since 1980, field and laboratory studies and computer simulations have revealed much of what happened 65 million years ago. The impact excavated a cavity about 100 kilometers in diameter, displacing some 100,000 cubic kilometers of debris, including the melted rock from the immediate impact, vapor, and solid debris. As the first cavity collapsed, a crater 170 to 300 kilometers in diameter formed (since it is deeply buried under younger sediments, it is difficult to be sure of the size). Beyond the massive earthquakes, the impact triggered tsunamis that sped out from the Yucatan. The blast effects incinerated everything within thousands of miles and extended into the western United States. Rocks blasted out by the impact heated on reentry through the atmosphere and triggered wildfires on many continents. But the most far-ranging effects were from the rocks vaporized by the impact. In North America the impact deposit from the Cretaceous-Tertiary event can be readily separated into two layers: a lower layer of material directly ejected from the impact and an upper layer of atmospheric fallout from material in the vapor-rich plume that rose far into the atmosphere and was then carried around the world. Only the upper, fallout layer is found in Europe, Africa, and the southern hemisphere, although it thins away from the impact site.

The dust of the vapor cloud obscured the sun and cooled the earth for months, probably shutting off photosynthesis for a lengthy period, and causing much of the extinction. Sulfur from the carbonate rocks in Yucatan would have been turned into sulfuric acid and then acid rain. How long this destruction lasted is unclear. Early workers suggested the dust cloud persisted for years, but later computer simulations showed that as the particles began to stick to each other they would rain out of the atmosphere more rapidly.

The site of the impact was unknown in 1980 and some geologists doubted it would ever be found. On the Moon and Mars the lack

of wind, rain, and active tectonics preserves craters for billions of years. Here on Earth the trace of even an immense impact are soon obliterated by erosion and buried by sediments. The surface of the Yucatan Peninsula in Mexico betrays few signs of the impact. But impacts do leave a footprint in gravity and magnetic patterns. The Earth's gravity and magnetic field vary across the surface of the earth. Mountain ranges have deep roots of low-density rock that project down into the higher-density mantle. This allows mountains to "float" on the mantle. This difference in mass between a mountain and the overall global average can be detected by aerial surveys of the gravity and magnetic fields, with the mountains showing up as a negative gravity anomaly: since the deep root of the mountains displaces higher-density mantle rocks. As a mountain erodes, the deep root rises to compensate, and the negative gravity anomaly still shows up. An impact alters the regional gravity and magnetic patterns much like a mountain range, and old, eroded craters can be found in the same way. Gravity surveys revealed an unusual circular structure in the Yucatan but only later was it identified as a possible impact structure. Today Chixulub had been widely accepted by geologists as the site of the Cretaceous-Tertiary boundary impact, although some controversy remains over whether it exactly corresponds with the mass extinction horizon.

Iridium was soon picked up at many other Cretaceous-Tertiary marine and terrestrial boundary sections around the world. But the analysis of iridium turned out to be far more difficult than initially expected. This was not terribly surprising, since geologists were looking for vanishingly small amounts of iridium, often at the absolute limits of what could be detected. In trying to detect such minuscule amounts, random fluctuations, small differences in analytical procedures, and inadvertent contamination can be the difference between finding iridium and coming up empty. Having a second, independent indicator of an extraterrestrial impact would obviously be ideal, particularly since some extraterrestrial objects, such as comets, are unlikely to have much iridium. Geologists soon established another sign of impact: a characteristic pattern of parallel fracture sets within mineral grains, particularly quartz. Commonly known as shocked quartz, these fractures are caused by the tremendous energy of impact and the associated pressure wave. Just as the unambiguous detection of iridium required careful laboratory work, reliably identifying shocked quartz also turned out to be more difficult than expected, and there have been many false reports of shocked quartz.

I have covered the effects the Cretaceous-Tertiary impact in so much detail for two reasons. First, we know more about this extinction and its likely causes than any of the other events, and second, because impact is also a possibility for the end-Permian event. The events of the end-Cretaceous provide useful comparison for what we might expect in the Permian.

The end-Triassic mass extinction 199 million years ago has been well studied in Europe, but the extent of the crisis in other parts of the world has been unclear. A rapid rise in sea level coincides with the elimination of some 53% of genera and 22% of marine families. Particularly affected were cephalopods (with octopus and pearly nautilus as modern representatives), brachiopods, clams, and some snails. Many of the Paleozoic groups that survived the end-Permian mass extinction finally disappeared. About 12% of vertebrate families also disappeared, and in the aftermath, dinosaurs took command of the land. Some paleontologists have championed the spread of anoxic waters as a cause and others have claimed evidence for an extraterrestrial impact but recent high-precision radiometric age dating of volcanic rocks along the east coast of North America, in Morocco, Spain, and Brazil has shown that the mass extinction coincided with a series of massive volcanic eruptions. These areas were then united in the supercontinent of Pangaea, and the volcanism may be associated with the opening of the Atlantic. The leading candidate for the trigger of the end-Triassic extinctions is this massive volcanism, known to geologists as the Central Atlantic Magmatic Province because it spans the Atlantic margin.

The next mass extinction in the series is a complex and still poorly understood episode 376 million years ago during the Late Devonian. Some 57% of marine genera and 22% of marine families disappeared during a series of events. Again, brachiopods experienced considerable extinction as did trilobites, corals, and other members of reef communities; bivalves and gastropods suffered relatively minor losses. In Europe, some paleontologists see evidence for at least three discrete extinction pulses; global studies are more equivocal. At least one extraterrestrial impact is known from the Late Devonian, but it does not correspond to any extinction horizons. Possible causes include spread of low oxygen waters, changes in the chemistry of the oceans, and climate change. But until geologists learn more about the extinction, it may be premature to consider the causes.

The second largest mass extinction brought the Ordovician Period to a close 439 million years ago. The trilobite-dominated communities of the Cambrian disappeared during the Ordovician Radiation, diluted by the rapid growth of the dominant Paleozoic communities with articulate brachiopods, crinoids, bryozoans, and some Paleozoic corals. These groups lived attached to the sea floor and filtered food out of the water (there was little, if any, life on land this early in animal history). Two discrete extinction events separated by perhaps 500,000 to 1 million years extinguished 60% of marine genera and 26% of marine families. Glaciation and global cooling were the most likely causes of this event. The extinction began with a rapid glaciation and consequent drop in sea level, and then as the glaciers melted, sea level rose rapidly and delivered anoxic, or low oxygen, waters into shallow seas and caused the second pulse of extinction. Brachiopods suffered particularly heavy extinction, as did trilobites, echinoderms and bivalves, and some corals. One of the most enduring curiosities of this episode is why it had such little long-term ecological impact. The various surviving groups produced many new species over the following 1–2 million years, and Early Silurian communities do not appear to be much different from those before the extinction.

Stephen Jay Gould made the great Cambrian explosion of animal life famous in his book *Wonderful Life*, describing the "weird wonders" of the Burgess Shale. The Cambrian Radiation marked the origins of diverse animal fossils, from the ever-popular trilobites through many early shelled organisms. The oldest recognized mass extinction in the fossil record occurred shortly after this, about 512 million years ago, near the end of the Early Cambrian. This event has only been recognized during the past decade and appears to have eliminated about 50% of all marine species, including many of the distinctive animals of the Early Cambrian seas. An odd, spongelike group called the archaeocyathids disappeared, as did some trilobites and a variety of tiny shelly fossils. The Early Cambrian was a time of rapid overturn in biodiversity, with high rates of extinction and origination. The disappearance of so many distinctive lineages at the close of the Early Cambrian suggests that something different happened at this point. Unfortunately we know so little about this event that we can say little about the likely causes.

This brief survey shows that there are many different ways of causing mass extinction: global cooling in the Late Ordovician, massive volcanism across the Triassic-Jurassic boundary, and the impact of an extraterrestrial object in the Late Cretaceous. Finally, the causes of two events, in the Late Devonian and Early Cambrian are unknown, and the series of Late Devonian events are much different from other episodes. At least among the great mass extinctions no evidence of a single, unified cause has been uncovered, although as we will see, suggestions persist of links among less drastic biodiversity crises.

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While the relatively abrupt changes in fossil were evident to John Phillips and his colleagues in the mid-1800s, these transitions appear to have been of little interest to geologists and paleontologists until the 1950s. I am still amazed that Phillips and several subsequent generations of geologists were so uninterested, but it simply never occurred to them to inquire into the events behind the extinctions.

Not all major boundaries in the geologic time scale are demarcated by mass extinctions. The suggestion that a mass extinction occurred at the end of the Triassic but not at the end of the Jurassic was primarily the work of the late Jack Sepkoski of the University of Chicago. While in graduate school at Harvard, Jack began the Herculean task of assembling information on the oldest and

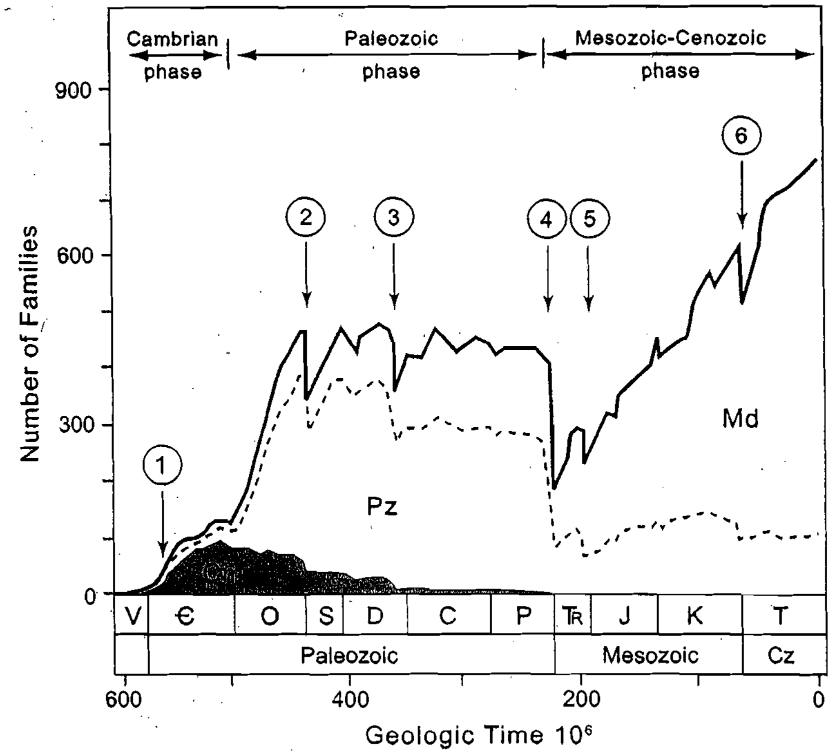

Figure 2.3 Marine diversity through the past 600 million years, modified from a figure by Jack Sepkoski (1984), based on his compendium of the first and last occurrences of marine families. The shaded area denotes the number of families assigned to the trilobite-dominated Cambrian Evolutionary Fauna. The dotted line shows families comprising the brachiopod-bryozoan-crinoid dominated Paleozoic Evolutionary Fauna. This fauna suffers particularly harsh extinction at the close of the Permian, and the bold black line denotes the number of families in the Modern Evolutionary Fauna, including snails, clams, crabs, and sea urchins. The circled numbers are the six great Phanerozoic mass extinctions: 1, Early Cambrian; 2, end-Ordovician; 3, Late Devonian; 4, end-Permian; 5, end-Triassic; 6, end-Cretaceous. The letters correspond to the geologic periods in figure 1.4. Redrawn from Sepkoski 1984.

youngest occurrence of all genera and families ever found as marine fossils. Some broad compilations had been attempted before, but in nothing like the detail Jack devoted to the task (figure 2.3).

In 2001 Richard Bambach and Andy Knoll of Harvard, both of whom will figure prominently later in this account, took another look at the data compiled by Sepkoski. They suggested that the pattern of mass extinctions was more complex. Although the Late Devonian and end-Triassic episodes showed up prominently in earlier studies, they remained enigmatic. Their diversity patterns are distinct: although their extinction levels are high, they are not as exceptional as for the end-Ordovician, end-Permian, and end-Cretaceous. The principal characteristic of the Late Devonian and end-Triassic episodes is a failure of origination rather than exceptional extinction, leading Bambach and Knoll to describe them as "mass depletion" episodes. However this new wrinkle in the story develops, the evolutionary impact of these events is certain. Well-developed reefs vanished for almost 100 million years after the Late Devonian, and the end-Triassic saw off some soft-bodied chordates (animals with a spinal cord, but in this case lacking bones), known as conodonts that are among the key index fossils of the Paleozoic and Triassic.[4]

But are mass extinctions truly different, or is there a continuum of extinction magnitudes between the end-Permian, the largest of the past 540 million years, and lesser episodes? Some extinction has occurred during every interval of geologic time. Dave Raup produced a fascinating chart arraying the magnitude of extinction (figure 2.4). This shows a continuum, downplaying any sharp difference between the mass extinctions and other times. Raup and Sepkoski identified another interesting extinction pattern in 1984 with a very different implication. Again using Sepkoski's magnificent compendium of fossil families, they described a cyclical pattern of about 26 million years to mass extinctions between the end-Permian and the present (figure 2.5). Some of the extinction events were very small, barely above the noise in the data, but the cycle encompassed the end-Triassic and end-Cretaceous mass extinctions, as well as several smaller but previously recognized biotic crises. We will return to this pattern in the final chapter, for it suggests there must be some underlying cause connecting these events, and, moreover, that at least some of these biotic crises may differ from the everyday extinctions in other intervals.[5]

The remainder of this chapter considers the various proposed causes for the end-Permian event. The possible villains, if you will. The scent of an impact is foremost in many people's minds, so we begin there before turning to other possible extraterrestrial events, and then to the massive flood basalts in Siberia and other types of volcanism and their possible association with climatic changes. This leads us to the role of changing position of the continents and their effect on biodiversity and how the rise and fall of sea level can modify the amount of available area for organisms to inhabit. We turn next to evidence from the carbon cycle for reduced oxygen in the oceans and the possible release of vast amounts of methane. The chapter concludes by describing the

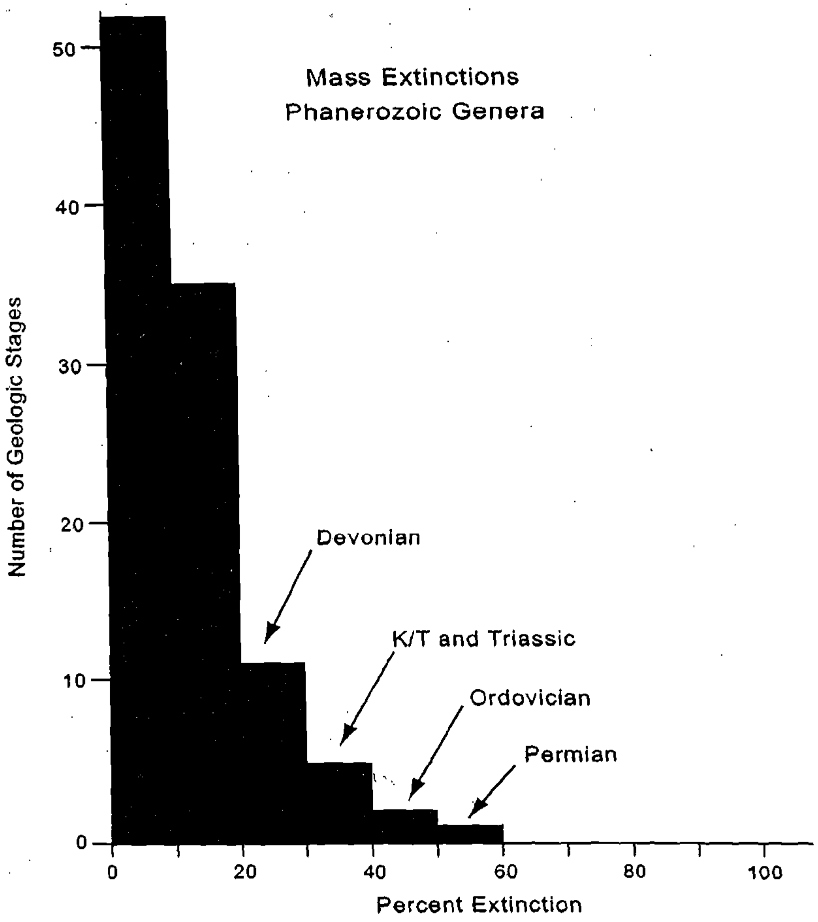

Figure 2.4 David Raup's depiction of extinction intensity, arraying the extinctions in each of the stages of the Phanerozoic by the magnitude of extinction. This shows no distinct differences between mass extinctions and the extent of extinction in other stages. After Raup (1991).

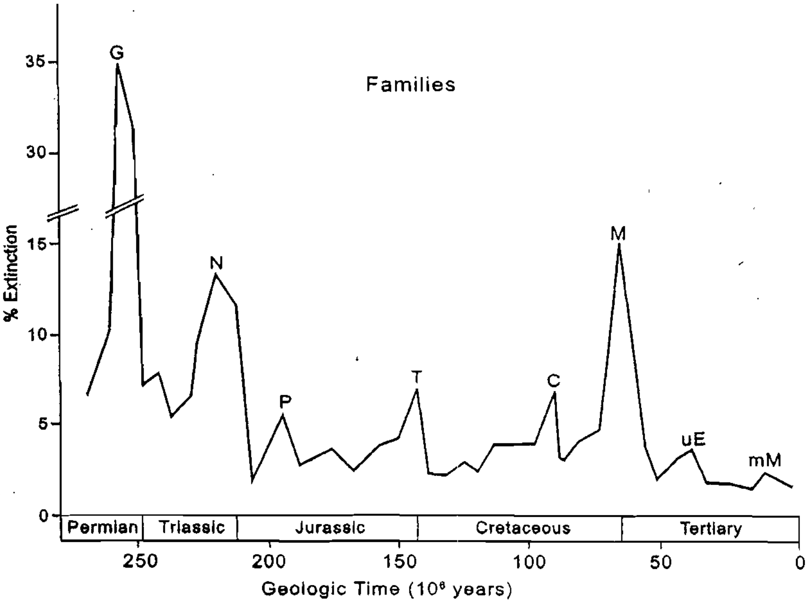

Figure 2.5 Apparent periodicity in extinctions from 250 million years ago to the present, based on peaks in the percentage extinction in Sepkoski's compendium of marine family diversity. Redrawn from Raup and Sepkoski, 1986, used with permission. Copyright 1986 AAAS.

specific predictions from each theory and the kind of evidence we must seek to evaluate them.

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Following the apparent success of the Alvarez hypothesis in explaining the end-Cretaceous mass extinction, the Permo-Triassic boundary was the obvious next place to look for iridium. Volcanic clays at the Meishan boundary sections in south China and another section at Wachapo Mountain, in Guizhou Province, revealed less than 0.5 parts per billion of iridium. Another study by a group of Chinese geologists based in Beijing reported up to 8 parts per billion of iridium from Meishan. Since the Alvarez group had reported abundances of about 8 parts per billion for the Cretaceous-Tertiary boundary, the work by the Beijing group appeared to suggest that a similar impact occurred at the Permo-Triassic boundary. Yet many attempts to repeat the results of the Beijing scientists proved fruitless. Neither the late Carl Orth at the Los Alamos National Laboratory in New Mexico, nor the group at UC Berkeley could replicate the Beijing claims. Orth's group reported levels of 0.002 and 0.024 parts per billion from splits of the same samples the Chinese group had analyzed. Such vanishingly small abundances are essentially insignificant and provide no evidence for impact.[6]

No one has worked out why the Chinese and U.S. labs got such different results. I asked Carl Orth about this shortly before he died and he suggested analytical differences between the two labs, or even very slight differences in the sedimentation rate between different places. Remember that Walter Alvarez originally undertook his search for iridium to look for differences in sedimentation rates.

Carl Orth and his colleagues did discover two very small peaks in iridium abundance in a core drilled through the Permo-Triassic boundary in the western Alps on the Gartnerkofel. The lower peak coincides with a sharp perturbation in the carbon cycle, and the second occurs higher in the section. The mass extinction is probably coincident with the lower shift in carbon. Pyrite (fool's gold) and other minerals occur with the upper iridium peak, evidence of an unusual chemical environment. Although an impact origin for the iridium could not be ruled out, the overall chemistry of the rocks strongly suggested that the iridium was concentrated by something other than an extraterrestrial impact. More recently a new group of impact experts led by Christian Koeberl in Vienna analyzed these rocks and again found no evidence supporting an extraterrestrial impact. Rather, the slightly elevated concentration of iridium and other elements occurs in a zone of anoxic deposition, which is known to concentrate the elements.[7]

The best proof of an impact would be a crater of the right age. In 2000 several geologists announced the presence of a possible impact structure in the Carnarvon Basin of western Australia, using gravity and magnetic data similar to that uncovered the Chixulub crater in the Yucatan. Australian ranches, or stations, make those in Texas seem puny, and this impact site was named the Woodleigh structure after the station where it was found. To my untrained eye, the gravity data look like a small bull's-eye with a central peak and two, or, if you sort of blur your eyes, maybe three, circular rings. The outermost ring is about fifty kilometers in diameter. High-speed photographs of raindrops falling on water show a rebounding peak from the center of the impact, surrounded by spreading rings. Most of the water in this thin conical peak is not from the drop itself, but from the underlying water. With a sufficiently large impact, the same thing happens on the earth. This central peak represents the resurgence of rock toward the center of impact. But on earth the central uplift can be frozen in place (although never with as sharp a peak as a raindrop). Just such a central peak appears in the gravity map of the Woodleigh structure. Arthur Mory of the Western Australian Geological Survey in Perth and his colleagues argued that the structure is an impact crater at least 120 kilometers in diameter, making it the fourth-largest impact crater known, although still a fair bit smaller than the structure in Yucatan.[8]

Geologists often have great difficulty determining the age of impact structures. Quite fortuitously, a 189-meter-deep well was drilled nearby and produced shocked quartz fragments characteristic of an extraterrestrial impact. Early reports of sediments from an Early Jurassic lake covering the crater, shales with Early Permian pollen in the crater, suggested the crater must be younger than Early Permian, but older than Early Jurassic. Mory and his colleagues provided other evidence the rocks were heated sometime between 280 and 250 million years ago, and suggested this was the age of the impact. So while the impact *could* have occurred at the Permo-Triassic boundary, Mory had no real evidence to connect it with the mass extinction. (This rather significant point was ignored by the press coverage, of course, showing that some science journalists are as susceptible to "spin" as those covering Washington.)

The Case of the Woodleigh Conundrum was resolved in when Wolf Reimold of the University of Witwatersrand in Johannesburg, and Chris Koeberl of the University of Vienna published a critical response to the Mory paper. They questioned the shocked quartz, the estimated size of the structure, and even whether it was produced by an impact. Both Reimold and Koeberl are respected impact geologists, so their concerns were influential. In response Mory and colleagues provided additional data on the possible shocked quartz and convincing evidence for an impact origin for the structure. More important, however, were new radiometric ages pointing toward an impact near the Devonian/Carboniferous boundary, 100 million years before the end-Permian mass extinction. While the Woodleigh structure may warrant further study as an impact structure, there is little reason to connect it with the Permian mass extinctions.[9] Even raising the crater might seem pointless as newer research has revised the earlier hypothesis of a Permo-Triassic date, but this is a cautionary tale to reserve judgment on putative impact features until they are well dated and their impact origin confirmed.

The need for caution continues as I write this book. Early in 2004 Luann Becker of the University of California at Santa Barbara proposed another possible Permo-Triassic impact structure, this time off western Australia where an unusual feature on the sea bottom, the Bedout structure, has garnered attention from geologists. Gravity data, and what have been interpreted as impact debris and impact melts, provide much of the evidence and a single radiometric date of 250.1 +/− 4.5 million years supported assignment of the feature to the end-Permian mass extinction.[10] The Chixulub impact at the Cretaceous/Tertiary boundary demonstrated that a large impact ejects vast amounts of rock into the atmosphere and may trigger massive tsunamis. Both the blanket of airborne ejecta and the jumbled debris of a tsunami are good evidence of impact. The Bedout structure itself, buried deep beneath younger sediment, is an uplifted region of rock evident on seismic imaging of the region. Becker and colleagues interpreted this as the central peak, similar to that in the Woodleigh structure, with the total diameter of the crater similar to Chixulub. It is safe to say that virtually every aspect of this report has been criticized by other impact geologists, from the evidence of impact debris to the quality of the radiometric dates. These doubts have raised strong questions about the significance of the Bedout structure to the Permo-Triassic story, a point to which we will return in chapter 8.

Curiously, the only possible shocked quartz ever reported from the Permo-Triassic boundary comes from eastern Australia, New Zealand, and Antarctica where Greg Retallack of the University of Oregon has been working. Greg is a brash Australian whose modus operandi is often to advocate the opposite of what everyone else believes (a salutary characteristic in science). I was amused in 1996 when he told me that he had found the "magic layer" with evidence of an extraterrestrial impact at the Permo-Triassic boundary. Yet no impact debris has been found in sections in Antarctica and in southeastern Australia; the levels of iridium were insignificant. Evidence for shocked quartz was also ambiguous, since Retallack's quartz grains were smaller and far less numerous than those found at most Cretaceous-Tertiary boundary localities. Although some Cretaceous-Tertiary boundary sites have low iridium levels and few shocked quartz grains, in the absence of any other evidence for impact at the Permo-Triassic boundary, the Oregon group eventually concluded: "Unlike the Cretaceous-Tertiary boundary with abundant evidence of a major impact in Yucatan and globally broadcast ejecta . . . the Permian-Triassic boundary yields only the scent of an impact. Yet, the much more severe extinction at the Permian-Triassic boundary demands evidence of a much larger impact if that were its primary cause. The magnitude and location of impacts at the Permian-Triassic boundary remain uncertain, so their role in Permian-Triassic extinctions remains to be demonstrated."[11]

But impact aficionados should not despair! In 2001 possible new evidence of impact at the Permo-Triassic boundary came from an unexpected source. Readers who were conscious during the 1970s may remember the propagation of geodesic domes across the landscape. Advocated by Buckminster Fuller, these hemispherical structures of intersecting metal rods were the tepees of the Age of Aquarius. In 1985 a group of chemists announced the discovery of a new class of carbon compounds—spheres of sixty or more carbon atoms linked in a lattice of hexagonal and pentagonal rings, the same architectural principle as Fuller's geodesic domes. Pure carbon comes either as graphite or diamonds, so the discovery of a third, previously unknown form of carbon was remarkable. Colloquially known as Bucky-balls, fullerenes have such interesting chemical properties that the three discoverers were recognized with the 1996 Nobel Prize in Chemistry.

Fullerenes can be produced by lightning strikes, forest fires, and meteorite impact, but how long they persist in the environment or in rocks remains uncertain. Reported fullerenes in Cretaceous-Tertiary boundary clays have been linked to catastrophic wildfires triggered by the impact. The discovery of fullerenes in Japanese Permo-Triassic boundary sections was also linked to wildfires, with the fullerenes preserved in soot particles. "Trust but verify" is even more of a principle for geologists than for diplomats (or at least presidents) and scientists always want important results confirmed by independent laboratories. Unfortunately, confirming the geological reports of fullerenes has proven difficult. Many fullerene reports have not been replicated at other laboratories, and the reported fullerene abundances are often close to the limits of detection. One study found an increase in hydrocarbons, which may mimic fullerene, but no evidence for fullerenes themselves. Some chemists were hardly surprised by the failure to replicate early reports. Fullerenes break down relatively quickly when exposed to air. Preservation of fullerenes for hundreds of millions of years may be possible, but only under extraordinary conditions.

Fullerenes were reported from Permo-Triassic boundary sections at Meishan in China and in southwestern Japan,[12] evidently concentrated in the volcanic clay marking the extinction (see chapter 3). When Luann Becker and her colleagues analyzed the ratio of helium to argon within fullerenes, they found a surprise. Fullerenes were absent from rocks above and below the extinction point. Fullerenes can capture other elements within the buckyball structure; hence the great fondness chemists have for them. Those that arrive on meteorites have a very distinctive ratio of helium to argon, reflecting the primordial ratio in the planetary dust cloud during the formation of the solar system. This ratio is very different from the helium to argon ratio on earth. By comparing the ratio of helium to argon in fullerenes from Permo-Triassic boundary beds to fullerenes from the Murchison meteorite, Becker's group was able to determine whether the fullerenes were formed on Earth, perhaps in a wildfire, or came from space. The critical question was whether the fullerenes could have been produced during an impact rather than being remnants from the origin of the solar system. Fullerenes only incorporate gases like helium and argon into their structure when the surrounding pressure is very high, far beyond the pressures possible on Earth even during an impact, and must have formed in the planetary gas cloud and later have been delivered to Earth. They argue that this is convincing evidence for an impact and suggest an object about nine kilometers in diameter (although there seems little real evidence for the size of the object).

Such a novel approach to impact raises a host of questions: Are the assumptions about terrestrial versus extraterrestrial sources sound? Are fullerenes actually stable enough to survive an impact? Can fullerenes be carried along in the waters that flow through rocks, and even be preferentially enriched in certain zones? All of these questions had to be faced by the proponents of iridium in the early 1980s. It was some time before most geologists accepted an extraterrestrial origin for the high concentrations of iridium at the Cretaceous-Tertiary boundary. In the same way, although fullerenes have been studied in many different types of rock, it is probably still too early to declare fullerenes conclusive evidence of an impact at the Permo-Triassic boundary.

Just as I was finishing this book, new evidence of possible impact appeared, again from sites in Antarctica and China, in the form of microspherules composed of iron-nickel-silica and possible fragments of a meteorite. While the scent of an impact may be growing stronger, the stench of massive volcanic eruptions has become overwhelming, so we turn now to the second large class of proposed causes: volcanism.

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Mass extinctions and the Alvarez hypothesis have piqued the interest of many scientists far beyond paleontology and geology, and few months go by without my receiving an email bearing yet another theory for the end-Permian mass extinction. One of my favorite Grand Unified Permian Theories comes courtesy of several Indian physicists. They linked the twin phases of the Permian mass extinctions at the end of the Middle Permian and the close of the Permian to a purported accumulation of weakly interacting massive particles (WIMPS) in the Earth's core. WIMPS are a form of hypothetical dark matter conjured up by some cosmologists to explain why galaxies have less observable mass than is required to explain their rate of rotation. If there is a great deal of hidden mass, everything will balance out and the cosmologists will be happy. (Personally, keeping cosmologists happy has never been high on my list of priorities, but I digress.) The Indian physicists proposed that an influx of high-energy WIMPS caused genetic damage and increased cancer rates in everything from plants to sponges to the therapsids of the Karoo. As the WIMPS accumulated in the core of the Earth they caused heating and eventually the eruption of a massive plume of very hot material from near the boundary between the core and mantle. Superplumes rise like a hot-air balloon through the mantle and eventually erupt at the surface where they may produce massive piles of volcanic rock. Thus cancer caused the first pulse of extinction and the eruption of the Siberian volcanism caused the second pulse (of which more, below). Changes in tectonics and anoxia in shallow marine waters completed the extinction process.[13]

Now I don't believe a word of this, but I do admire the sheer creativity: virtually all of the features of the two extinction pulses are incorporated, without worrying overly much about the details. Leaving aside the issue of why such hypothetical WIMPS should accumulate in the Earth's core, and how they would trigger a mantle plume, it would be easy to dismiss this scenario as a bit crazy. Much of this model is beyond the realm of science, but there are a few testable claims. Other elements are shared with other extinction scenarios and so do not provide any unique predictions. Physicists and geophysicists are better able to judge the plausibility of WIMPS heating the core and inducing plume formation, but the purported increased cancer rates during the Capitanian extinction are nicely undetectable in the fossil record. On biological grounds, mass extinction due to cancer is implausible and is unlikely to produce the different extinction patterns (why would some animals with a heavy shell, such as brachiopods, suffer considerable extinction, while molluscs with an equally heavy shell escape?). On average, one should expect higher cancer rates among the most exposed organisms. Thus terrestrial and shallow marine animals should have been the most affected. Species with large population sizes should be the most likely to survive. As we will see in chapters 5 and 6, different groups varied considerably in how much extinction they suffered, but the selectivity was not in the direction required by the WIMP hypothesis. Yet the WIMP hypothesis addresses two very real issues: was there a linkage between the two pulses of extinction in the latest Permian, and what triggered the massive outpourings of basalt in Siberia?

Until recently geologists were more comfortable with slow, inexorable processes rather than Las Vegas spectaculars, and the immense size of some flood basalts led geologists to expect that they formed over millions of years. Over about 1 million years an area about the size of the continental United States was inundated with at least 4 million cubic kilometers of material, covering the region to a depth of 100 to 6,000 meters or more. The environmental effects of so much volcanism, incessant clouds of dust, acidic vapors, and heat are difficult to contemplate today. We have no experience of eruptions on the scale of the Siberian flood basalts, the largest to erupt on any continent in the past 600 million years. The 1783 Laki eruption in Iceland generated 12 cubic kilometers of material in about eight months. But massive continental flood basalts seem to operate by different rules: a single flow from the Cretaceous-Tertiary Deccan flood basalt in India generated nearly 1,000 cubic kilometers in perhaps only a few weeks. Some volcanic ash and other debris are associated with the Siberian flood basalts so at least some of the eruptions must have been explosive, but most of the eruptions would have been much more like those of Kilauea in Hawaii than Mount Pinatubo in the Philippines, or Mt. St. Helens in Washington.

Basalt forms from a viscous magma that tends to flow during a flood basalt eruption, although some explosive eruptions have occurred. If basaltic eruptions are large enough, the magma will gradually fill in valleys and lowlands much as honey fills in the

roughness of an English muffin. The flowing basalt obliterates the countryside, preserving it beneath a smooth, undulating surface, hence the name *flood basalts.* Flood basalts can cover a vast area with flows as much as a mile in thickness.

Today the main area of the Siberian flood basalt covers only about 675,000 square kilometers, but estimates of original extent continue to grow. Russian geologists have identified at least four distinct centers of volcanism. The Noril'sk region in northwest Siberia is one of the most easily accessible and thus well-studied zones. Here, volcanic material 3,700 meters thick includes eleven discrete eruptive sequences and forty-five separate flows. A single flow may be tens to hundreds of meters thick with layers of volcanic ash (tuff) and other volcanic debris several meters thick between the flows. One tuff layer 15 to 25 meters thick has been traced across 30,000 square kilometers. In another region, Maymecha-Kotuy, geologists have estimated the total thickness of volcanics at over 6,500 meters, or almost four miles. Erosion, burial, and the formation of the Ural Mountains have destroyed the western margin of the volcanics. The basalts also extend into central Kazakhstan. To the north remnants are found in the Taymir region, and kimberlite pipes to the east (the source of diamonds) represent an early, very explosive phase of the eruptions.[14] The total region of volcanic material covers much of Siberia from the Urals east to Lake Baikal and south into Kazakhstan (figure 2.6), an area of about 7 million square kilometers (2.7 million square miles)—almost equal to that of the continental United States.

Volcanic eruptions incorporate radioactive elements that decay over time, as discussed in more detail in chapter 4. This decay produces a sort of radiometric clock that allows the date of the eruption to be calculated. Recent dating of the Siberian flood basalts has produced ages ranging between 252.2 and 251.1 million years ago, indicating the flood basalt erupted in 1 million years or less. These dates are essentially identical with other, high-quality radiometric studies of Permo-Triassic volcanic ash beds in south China, suggesting the events were contemporaneous.

For the moment, let us assume that the dates for the flood basalts and the mass extinction overlap, occurring during the same mil-

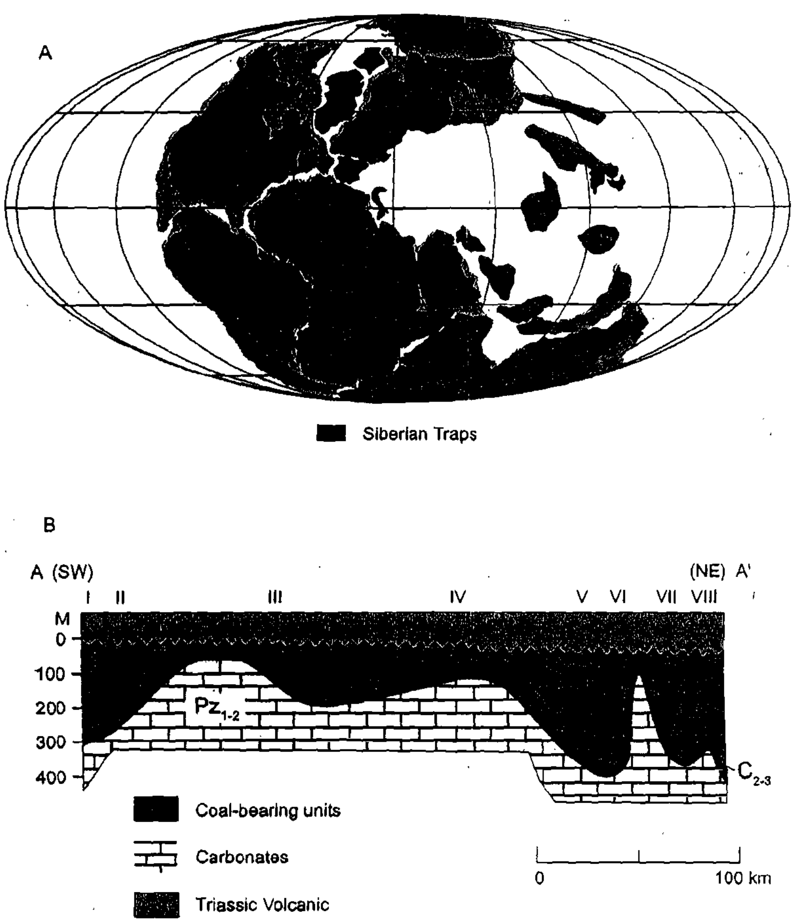

Figure 2.6 The Siberian flood basalt. A: reconstruction of Pangaea at the Permo-Triassic boundary showing the position and extent of the Siberian volcanism. B: a generalized cross-section across Siberia showing the coal-bearing units beneath the volcanics. A is based on Scotese and Langton (1995); Ziegler and Charles (1990); and Ziegler et al. (1998); B is based on Czemanske et al. (1998), reproduced with permission from *International Geological Review* 40(2): 95–115, © V. H. Winston and Son.

lion-year period. Coincidence? Perhaps, but a pretty unusual one. Coincidences plague any historical analysis and the correlation of two events in time does not prove a causal connection between them. The human genome was deciphered the same year George Bush the younger was declared president, but it is hard to see any connection between the two events. What we really want to know is how the flood basalt eruption could lead to the extinction of so many species, a subject to which we will return in chapter 8.

Ash beds near the Permo-Triassic boundary in south China reflect a different style of volcanism. My colleague Professor Yin Hongfu of the China University of Geosciences at Wuhan has long led one of the major Chinese groups studying the extinction. There are many volcanic ash beds in the Chinese sections spanning the Permo-Triassic boundary; a particularly nice ash bed coincides with the mass extinction. Unlike the flowing flood basalts, volcanoes along plate margins where oceanic crust is being subducted into the earth behave very differently. The subducted slab melts and the large amount of silica produces a thick, gummy magma that often erupts explosively. Subduction-derived basalts also have distinctive chemical signatures. From this we know that the south China ash beds were not related to the Siberian flood basalts, but to volcanoes along the southern margin of China. Even the small amount of ash and gas produced from the eruption of Mt. Pinatubo showed that stratospheric winds distribute ash globally. Some of the latest Permian volcanic eruptions in south China were far larger than Mt. Pinatubo, or any in recorded human history. This led Professor Yin to propose that the eruptions blotted out the Sun, cut off photosynthesis, and triggered the mass extinction. But there are many massive volcanic eruptions documented in the rocks of south China, and only one corresponds with any loss of species.

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Continental drift and its impact on the earth's biota through climatic change form the third class of extinction hypotheses. Despite having spent my teenage summers in the incredible rocks of the southwestern United States, I entered college woefully ignorant of geology. This deficit was quickly mended through a freshman seminar on plate tectonics: the horizontal movement of plates that comprise the upper 10–40 km of the earth, their creation along midocean spreading centers and their destruction as they plunge into the earth and gradually melt. That first course also provided my introduction to the end-Permian mass extinction, when I discovered the work of Jim Valentine relating plate tectonics and changing positions of the continents to changes in factor controlling the total number of plants and animals on the globe was the number of biologically independent regions, or biotic provinces. All other things being equal (not that they ever are), the more biotic provinces, the greater total global biodiversity. Jim's insight was to realize that the dance of the continents should play a profound role in modulating biodiversity over millions and tens of millions of years by changing the number of provinces and climatic patterns.

Imagine that three continents collide, each containing separate species of rabbits. Before the collision each rabbit species has a continent to itself, but after the collision the rabbits must compete with each other. One expectation from ecology is that only the best-adapted rabbits will survive on the new, larger continent. The other two rabbit species will either become extinct or find a different way of making a living. If the continents are large enough, there may be many species of rabbits in different habitats, but the same logic applies. This is, incidentally, the reason that conservationists are so concerned about the spread of non-native species around the world: such biotic homogenization reduces biotic provinciality just as surely, and far more rapidly, than continental drift. Conversely, the breakup and dispersion of continents should increase biological diversity as the species on each continent follow independent evolutionary trajectories.

Continents may drift into different climatic regions but they can also modify climate in less obvious ways, for example by changing oceanic currents. As the Isthmus of Panama formed a few million years ago it closed off a westward equatorial current, turning the Caribbean into a large gulf. The currents that once flowed through the Isthmus were forced to turn north, considerably strengthening the Gulf Current. Great Britain and Europe have greatly benefited as this northward direction of warm water into the Atlantic has made them far more habitable than would otherwise be the case. Jim Valentine reasonably concluded that such continental movements must be important controls on long-term biodiversity patterns.

When Jim was considering these issues during the early 1970s, reconstructions of past continental positions were fairly primitive.

The revolution in plate tectonics was less than ten years old and the supercontinent of Pangaea was believed to have formed near the end of the Permian (as shown in figure 2.6). Pangaea was an agglomeration of almost all the continents, formed by a collision between a southern mass of continents (Antarctica, Africa, South America, India, Australia, and bits of southeast Asia) known to geologists as Gondwana, and a northern mass (North America, Europe and Siberia), or Laurasia. The formation of Pangaea suggested to Jim and his colleague Eldredge Moores that a reduction in biotic provinciality caused the mass extinction. In essence, as Pangaea grew the homogenization of previously distinctive plants and animals drastically reduced biodiversity.

The formation of such a large landmass would influence global climate, which might also have contributed to the extinction. Siberia and Chicago have more severe climates than New York or London: the winters are colder and more miserable, and the summers warmer and more humid. This greater seasonality in continental interiors is a simple consequence of the ameliorating effects of the oceans. More energy is required to change the temperature of a given volume of water than the same volume of air. Thus oceans moderate the climatic fluctuations of coastal areas relative to the interior. Large lakes, incidentally, can have a similar effect (so Chicago would be even more miserable in February without Lake Michigan). Central Asia has very pronounced fluctuations in climate today, with cold winters and very hot summers, but these variations are mild compared to estimates for the center of Pangaea. Since we know from fossils that plants and animals did survive across Pangaea, large lakes may have existed in central Pangaea to modify the climate.

The increasing seasonality caused by the formation of Pangaea should also affect animals along the coastline. By impoverishing the ecosystems and changing current and climate patterns, Valentine and Moores suggested the supply of nutrients might have become more uneven, possibly leading to the disappearance of groups with very specialized nutrient requirements. Generalized species capable of feasting on whatever resources were available would increase. By this model, the formation of Pangaea should have caused a loss of biotic provinces, an increase in climatic variability, and an increase in the variability of nutrients, all contributing to the mass extinction.

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One of the most vexing features of the Permo-Triassic boundary is how hard it is to find. Permian and Triassic marine rocks are not uncommon in many parts of the world, yet few rocks were deposited during the transition between the two. This paucity of marine rocks was evident in the late 1960s and led Norman Newell of the American Museum of Natural History, one of the great paleontologists of the twentieth century and a founder of the more biological approach to paleontology, to invoke a global drop in sea level as the cause of the extinction, the fourth group of extinction scenarios. Why a drop in sea level should cause a mass extinction at first seemed obscure; Newell's paper and earlier work had suggested that regression could cause extinction by crowding species into less space. In 1967 Robert MacArthur and E. O. Wilson penned a short book that has become one of the classics of ecology: *A Theory of Island Biogeography*.[16] The isolation of islands makes them ideal systems for studying ecology, including the processes that control species diversity. MacArthur and Wilson argued that the number of species on an island reflected a balance between the immigration of species from the mainland, and the loss of species on the island due to competition with other species. From this it followed that small islands and those far from the mainland should have fewer species. Converting the model to evolutionary time replaces immigration with speciation and suggests that the species diversity on islands (and by extension other areas) should reflect a balance between speciation and extinction. The balance between these processes will be determined by the size of the island.

Extending this theory into the fossil record implies that since fluctuations in sea level alter the area of the shallow marine continental shelves occupied by most marine plants and animals, a drop in sea level should reduce shelf area, increase competition, and cause species extinction. During the 1970s many biologists believed that the relationship was nearly linear, so that the change in species diversity would correspond to changes in area. If, as many geologists argued, the end-Permian drop in sea level was so great that it virtually completely eliminated the deposition of marine rocks anywhere in the world, then a significant mass extinction was almost inevitable,[17] although predicting the size of the expected extinction turns out to be rather more difficult.

In principle, it should be straightforward to take the change in the area of shallow seas caused by a drop in sea level and determine how many species should become extinct. But while geologists could gauge the vertical extent of the change in sea level (with estimates varying between 200 and 280 meters), translating this into area is far more difficult. The change in area depends on how much of the continents are flooded and the slope of the continental shelves. The ice ages of the past few million years generated sea level changes of hundreds of meters but relatively little extinction because the oceans covered so little of the continental shelves: extensive changes in sea level were not translated into much actual change in area. Moving to the Late Permian, the efficacy of this model depends on the slope of the continents during the Late Permian, something we cannot readily determine.

If we assume for the moment that the estimated drop in sea level is correct, another approach to understanding the extinction is to ask what could trigger such a significant drop in sea level. Although sea level rises and falls for a variety of reasons, and on a variety of time scales, the change at the end of the Permian appeared to be one of the largest in the past 600 million years. Moreover, this drop is followed by a very fast rise in sea level, one of the most rapid known. This pattern suggested to Steve Stanley of Johns Hopkins that the extinction and the drop in sea level could be explained by a widespread continental glaciation.[18] Glaciation causes extinction as water is removed from the oceans to form ice, reducing the amount of shallow continental shelf, and as plants and animals have to migrate toward the equator to escape glacial conditions. Species unable to migrate may perish. Stanley cited other geologic factors to support this idea, including Late Permian glacial debris found in Siberia and in eastern Australia, the extinction of tropical reefs, which commonly suffer during glaciations, and the paucity of limestone deposition. Glaciation appears to have been the primary cause of the second largest mass extinction at the close of the Ordovician, lending credibility to the suggestion. There is little evidence for Late Permian glaciation sufficient to cause the estimated drop in sea level, raising doubts about the role of glaciation in the extinction.

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By the early 1990s several geologists began to question the accepted wisdom that sea level had dropped at the end-Permian extinction. Tony Hallam and Paul Wignall have most fully developed this view based on Hallam's earlier work on the end-Triassic mass extinction.[19] They trekked through China, Pakistan, the Alps, and elsewhere, carefully analyzing the changes in fossils and the types of rock formed during the extinction. These studies considered relatively few species and did not analyze the data statistically, but their data were convincing. The pattern of rock deposition revealed that sea level had been rising—challenging the views of pretty much every other geologist working on this issue.

But how does rising sea level kill things? This reversal in perspective leads to the fifth group of extinction scenarios, a cluster of three hypotheses all invoking a drop in levels of oxygen in the ocean, or anoxia. Hallam and Wignall focused on the rocks deposited just above the Permo-Triassic boundary. Earliest Triassic communities have few species, although the numbers of individuals in any one species may be enormous, running to millions or tens of millions of individuals. Such a skewed distribution is typical of highly stressed environments or postdisturbance settings when opportunistic, weedy species dominate. Indeed some of the fossils represent just such opportunistic groups. *Claraia*, first introduced in chapter 1, is a very thin scallop commonly found in low-oxygen waters, as is the brachiopod *Lingula*, another common species in earliest Triassic rocks. The very thin, rhythmic beds of Early Triassic limestones often are produced in environments where no worms and other burrowers were present to burrow through the mud, mixing the sediment and destroying fine laminae. The rocks also have peculiar chemical patterns that convinced Hallam and Wignall that rising sea levels brought very low oxygen, or dysaerobic, waters into shallow water. Most marine animals are adapted to normal oxygen levels, and if the amount of oxygen in the water drops too low, they essentially suffocate. Since the low oxygen waters will reach localities far out on the continental shelf before the waters reach farther inland, we should be able to trace the migration of the extinction with the rising, anoxic waters.

Anoxia figures in a different extinction model proposed by my colleague at the University of Tokyo, Yukio Isozaki, based on fieldwork in Japan and British Columbia. Sections across the Permo-Triassic boundary in Japan represent scarce bits of deep ocean sediments, and Yukio has focused his research on events in the deep sea. The recycling of plate tectonics destroys most oceanic crust, but as an oceanic plate is driven beneath a continent, slivers of the oceanic plate are often smeared onto the side of a continent. (The technical term for this is *obducted*, to contrast with *subducted*. Wonderful word, *obducted*.) Particularly common in these slivers are deep-sea cherts produced from the constant rain of siliceous microfossils. (Quartz is a highly crystalline form of silica, while chert and agate are microcrystalline silica, while glass and obsidian are amorphous or noncrystalline silica.) When deep ocean waters and sediments contain some oxygen, the resulting chert is a dark brick red as iron reacts with the oxygen. Above and below the Permo-Triassic boundary the cherts are dark red, but the boundary itself lies in dark gray to black cherts and carbon-rich claystones, signifying a lack of oxygen. The Pacific was actually much wider in the Permian than today (since the Atlantic didn't exist), and the discovery of similar rocks in Japan and British Columbia suggests that the entire deep ocean may have been anoxic for perhaps 20 million years.[20]

An anoxic deep ocean is a very odd thing to contemplate. Today upwelling currents bring nutrients from the deep sea into shallow waters, producing some of the richest ecosystems in the oceans. Other currents form as cold water sinks near the poles and drives toward the equator. Together these processes mix the ocean and ensure some oxygen even in the deepest levels. If Yukio is correct, no mixing occurred in deep oceans across the Permo-Triassic transition. Instead, the oceans must have been stratified, with an oxygen-rich surface ocean isolated from an oxygen-poor deep ocean. In Isozaki's extinction model, the stratified ocean develops near the end of the Middle Permian, triggering the first pulse of extinction, and then reaches a peak at the Permo-Triassic mass extinction, before gradually dying away in the Early Triassic. Thus this single hypothesis links two pulses of extinction and the long delay in the recovery of biodiversity after the mass extinction to a common cause. Critically, the deep-water persisted for perhaps as long as 10 million years.

Just as medicine has developed CAT scans, cardiac stress tests, and all manner of noninvasive imagery to measure the relative health of our bodies, geologists have developed a range of tools to chronicle the health of the earth through time. Identifying changes in the flow of carbon through the earth, oceans, and atmosphere is a powerful tool for tracking changes in the health of the earth. The end-Permian mass extinction coincides with an abrupt shift in carbon isotopes, evidence of a massive change in the carbon cycle. How we study these changes will be discussed in more detail in chapter 7, but a brief disquisition may help to explain the next two models.

Carbon comes in several different isotopes. Each isotope has the same number of protons in the nucleus but differs in the number of neutrons. Some isotopes, including carbon-14, are unstable and spontaneously decay to more stable isotopes (in this case nitrogen-14). During photosynthesis, the lighter isotope of carbon, carbon-12, is taken up in preference to carbon-13, so plants and the animals that feed off them have more carbon-12 than the average ratio in the atmosphere. This enrichment of organic material in carbon-12 continues into any organic material resulting from the decay of plants and animals, including humus and peat in soils, oil and organic material in rocks. This produces two large reservoirs of carbon differing in their ratio of carbon-12 to carbon-13: an inorganic reservoir and an organic reservoir enriched in carbon-12. Photosynthetic activity in shallow marine waters preferentially removes carbon-12 leaving the surrounding waters with a greater amount of carbon-13. Shells and skeletons record the ratio of the waters when they are formed, so by analyzing the ratio of carbon-12 to carbon-13 in a series of fossils, geologists can track changes in this ratio.

If that was all there was to the carbon cycle, the National Science Foundation would not have spent tens of millions of dollars over the past few decades equipping geochemists with the latest in spiffy new mass spectrometers to measure these isotopic changes. In fact, the changing ratio of carbon-12 to carbon-13 is a very sensitive indicator of changes in the carbon cycle. Comparing the carbon ratio between shallow waters and deep waters across the Cretaceous/Tertiary boundary shows, for example, that photosynthesis virtually disappeared during the mass extinction. The changing ratios may also reveal major changes in the amount of carbon added or removed from the organic carbon reservoir. As discussed in chapter 7, with a few assumptions geochemists can determine the amount of carbon that has shifted between one reservoir and another and from this the most likely sources of carbon.

The abrupt shift in the ratio of carbon-12 to carbon-13 at the Permo-Triassic boundary suggests that a large volume of organic carbon was added to the oceans and atmosphere (as I will discuss later, the rate of burial of organic carbon might also have dropped). But the curse of carbon isotopes is that many different processes can produce the same pattern. Give a bunch of PhDs data and few limits on their creativity, and something akin to chaos is the unremarkable result. Consequently, many of the disagreements over the cause of the mass extinction are really a debate over the cause of this shift in carbon isotopes. The following two ideas are based almost exclusively on differing views of the carbon isotopic evidence.

Some of my most significant contributions to science reflect my own stupidity. In 1994 I was at a meeting with Andy Knoll of Harvard and John Grotzinger of MIT. I showed a slide of a stromatolite (a rock with many very thin layers produced by microbial activity). John nudged Andy and said, "That's not a stromatolite, it's an inorganic precipitate." I would choose the wrong slide to show before the only two people who could tell them apart. Following my talk they descended on me like a pair of hungry wolves (well, to the extent that a couple of distinguished Harvard and MIT professors can act like hungry wolves). John and Andy wanted to know where I had taken the photo and got very interested when I told them that it was from near the top of Guadalupe Peak, the highest point on the Permian Reef in West Texas. These sediments may have been laid down during the earlier, Guadalupian mass extinction.

In his work on 2-billion-year-old rocks from Canada, John demonstrated that stromatolites could form directly through precipitation of carbonate from the ocean, not just by microbial activity, as most paleontologists believed. The unusual chemical conditions required for this were common a billion or more years ago, but are much less common in younger rocks. The precipitates, the carbon isotopic shift, and a new perspective on the patterns of extinction and survival among marine species led Andy, John, and their colleagues to a very novel stance on the extinction.[21] They made two points: First, that a detailed analysis of the patterns of extinction and survival suggest that more metabolically active species were more likely to survive than those groups that lacked such active metabolism. What does metabolically active mean? Humans have a higher rate of energy use than sloths; thus they are more metabolically active. In the oceans, clams, snails, and crabs, for example, are more metabolically active than corals or brachiopods. Second, they proposed that carbon dioxide poisoning was the trigger for extinction. In other words, a vast amount of carbon dioxide was released into the oceans and atmosphere and essentially poisoned the animals. The source of carbon dioxide is difficult to explain, but the deep-water anoxia described by Yuchio Isozaki provided a clue. They followed Isozaki's claim that the deep oceans had been stagnant during the Late Permian, and proposed the buildup of massive volumes of carbon in these stagnant, deep waters. Such a stagnant ocean is inherently unstable, and eventually something will cause it to overturn, releasing the carbon as carbon dioxide. In their model the onset of glaciation shifted current patterns in the oceans, triggering the release. Following their 1996 report, the *New York Times* drew a bad analogy between this model and the great burp of carbon dioxide from Lake Nyos in Cameroon on 26 August 1986 that killed about 1,700 people. In fact, Andy and

colleagues did not argue for such a convulsive burst, but more for a long slow fizz, with the mode of extinction carbon-dioxide poisoning rather than asphyxiation, as in Lake Nyos.

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It took me quite a while to understand the data on carbon isotopes from the Permo-Triassic boundary, and what little understanding I do have is thanks to the late Bill Holser, a geochemist at the University of Oregon who patiently tried to explain them to me during the early 1990s. As Bill's teaching began to sink in, I realized that none of the then current extinction models adequately explained the shift in carbon. This leads to the sixth extinction model. Picking up on suggestions by Euan Nisbet of the University of Edinburgh and others, in 1993 I proposed that the drop in sea level could have triggered the release of a large amount of methane from sediments on the outer continental shelf. Some bacteria produce methane rather than oxygen as a by-product of feeding off organic material, and in the ocean below about 300–500 meters methane can build up in the sediment as a sort of slush. The high pressure causes water to freeze at higher temperatures, but this produces cavities in the ice. These cavities fill with methane, producing methane hydrates. Oceanographers have become quite fond of them because the ices burn when touched by a flame, producing no end of amusement. The methane is stable in deep sediments because the pressure of the overlying water stabilizes them, but if the pressure drops, either because sea level drops or because some one punches a drill core into the ocean bottom, methane can be released to the water and eventually the atmosphere. Methane is a much more powerful greenhouse gas than carbon dioxide but in the atmosphere it normally dissociates to carbon dioxide in ten to twenty years. Nisbet suggested that the release of methane hydrates as sea level dropped during the recent glaciations reversed the climatic cooling, warming the globe and ending the glacial phase.

It took no particular insight on my part to realize that if major drops in sea level during the ice ages had released methane, the same thing was likely to have happened during the end-Permian sea level regression. The drop in sea level leads to release of gas hydrates, triggering the shift in carbon isotopes and producing global warming and extinction, but I was never entirely convinced that methane release was sufficient to explain the entire extinction.

To summarize the various hypotheses, we first have the possibility of the impact of an extraterrestrial object with the earth, as in the end-Cretaceous mass extinction. The second hypothesis involves the climatic consequences of the massive flood basalt volcanism in Siberia, and suggestions that the volcanism was somehow caused by an impact. Third, the formation of the supercontinent of Pangaea during the Permian may have caused biotic homogenization, just as is happening today, and gradually reduced biodiversity. The formation of Pangaea is one of the possible explanations for a drop in sea level at the Permian-Triassic boundary, the focus of the fourth group of extinction hypotheses. Here, a reduction in the area of shallow seas may have caused extinction, and Stanley suggested this could have been caused by a glaciation. Fifth is a set of three independent hypotheses invoking oceanic anoxia. Wignall and Hallam argue from detailed field studies that any drop in sea level was over by the extinction, and rising seas brought anoxic waters into shallow seas. Isozaki is more concerned with the growth of anoxic waters in the deep ocean, which Grotzinger, Knoll, and Bambach employed in their model of carbon dioxide poisoning. Finally, the sixth model was my suggestion that the release of vast amounts of methane from the continental shelves may have caused global warming and other climatic effects, leading to the extinction.

Each of the theories outlined above proposes a single primary cause for the mass extinction. Subsidiary causes trigger the extinctions, but each flows from the primary trigger. Life would be much easier if complex events had single causes, but the lessons of history are otherwise. The causes of most complex historical events are notoriously difficult to pin down, and the same is likely to be true of events in the history of life. In 1993 I suggested that methane release combined with several independent factors to trigger the Permo-Triassic extinction. I christened this the *Murder on the Orient Express* hypothesis, after the Agatha Christie murder mystery where all the suspects perpetrated the crime (although in Dame Agatha's novel the victim deserved his fate, while the brachiopods most assuredly did not). The chief drawback of this proposal is that it is very difficult to test, leading a colleague of mine to call it "Erwin's kitchen sink hypothesis" (he was not being complimentary). The difficulties in testing such ideas are not a priori a reason for dismissing them.

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Scientists have done a great marketing job convincing the public that we are objective seekers of truth, dispassionately weighing the evidence in our undying and noble quest to understand how the world works. Mr. Spock from *Star Trek*, but with a beard. The reality is that scientists are often opinionated, egotistical mavericks trying to determine how the world works while generally having a bit of fun along the way. Like many other people some scientists are also sure that we are right and anyone who disagrees with us is wrong. This is not to say that scientists do not change their minds. We do, if only under duress. Some of the best scientists are most willing to change their minds. But research is often a battlefield between contending egos, uncomfortably constrained by reality. Fortunately for the enterprise, scientists as a community have generally agreed on a series of methods to explore that reality, and ultimately it is this evidence that allows us to test differing views about how the world works. In the remainder of this chapter I summarize the explicit tests that allow us to evaluate these hypotheses.

Testing the impact proposal for the end-Permian mass extinction is easy, at least in principle. In fact, dozens of such tests have been conducted in the past two decades, and most have failed, with the possible exception of the recent discovery of fullerenes, meteorite fragments, and microspherules. Research on the Cretaceous-Tertiary boundary suggested we should search for such signs of impact as increases in the abundance of specific elements, particularly iridium, shocked quartz, diagnostic sedimentary deposits formed by the material ejected from the crater, and possibly fullerenes and other impact debris. The search for all of these features will continue, with increased attention placed on testing the reliability of the fullerenes. The work of Luann Becker and colleagues on fullerenes will have to be replicated by other labs, and similar evidence sought at other boundary localities. Geologists will also want to learn more about the origin of the fullerenes, how they may move in sediment, and if the helium and argon evidently encased in the fullerenes is truly an extraterrestrial signal. New investigations of the Bedout structure off Australia will be needed to test suggestions that it is an impact structure, and provide reliable estimates of its age; early reports are not encouraging. Furthermore, if the extinction was due to an impact, the event must have been virtually instantaneous and global, involving land and sea.

Three primary questions face proponents of a connection between the Siberian flood basalt and the mass extinction: First, do the radiometric ages for the PT boundary and the flood basalt really overlap? As these ages are refined, the correlation may fade and with it the link to the mass extinction. Second, what caused the eruption of the flood basalt? Greater understanding of how flood basalts form is essential to testing the suggestion that a massive extraterrestrial object triggered the eruptions. Understanding their source is not critical to establishing a link to the mass extinction but may reveal whether an underlying cause was present. Finally, there remains the issue of the linkage between the eruption and the extinction. This is the most difficult question, and parts of it may be impossible to resolve, but if the correlation between the flood basalt and the mass extinction withstands further scrutiny, the causal connection between them demands attention. Correlation is not causality.

Perhaps one way to examine the connection between massive volcanic eruptions and the extinction is by comparing the effects of volcanic eruptions of a similar size to the eruptions at the Permo-Triassic boundary. The South China volcanism is of similar magnitude to several well-studied volcanic eruptions in the past 100 million years. In addition, ash beds from many other large eruptions are preserved in Late Permian and Early Triassic rocks in south China, providing an opportunity to examine the fossil record above and below them. If volcanic eruptions were a major factor in the mass extinction, we would expect to see a stepwise extinction, with each step at an ash bed.

The Valentine-Moore hypothesis requires that the extinction occurred over millions of years as Pangaea formed. The pace of

the extinction must match the slow drift of the continents, an
the pattern of extinction must correspond to the onset of collisio
between continental regions. With an adequate fossil record, paleontologists should be able to track the intermingling of fauna
and resulting extinctions. One test of this model is to determin
whether the mass extinction and the formation of Pangaea happened at the same time, or whether the mass extinction occurre
more rapidly than the slow movement of the continents.

A number of tests for the species-area effect are available. Thi
model requires that the drop in sea level was contemporaneou
with the extinction. If they are out of phase, particularly if sea leve
is rising rather than falling, the hypothesis fails. Other information is available to test the model by looking at the effects on biodiversity of other changes in sea level and through recent studie
of the species-area effect.

As continental glaciers grow water is removed from the oceans
reducing sea level. If glaciation were responsible for the mass extinction the drop in sea level should correlate with the peak of extinction, and with geological evidence for glaciation near the poles
We should also expect that the rate of the regression and subsequent rise in sea level would be similar to other glacial sea-leve
changes. If changes in sea level do not correlate with the extinction
or if the change in sea level is significantly slower or faster than i
typical of glacially induced changes, we could reject this model.

The various anoxia models make very specific predictions abou
the nature of the extinction. Both the Hallam-Wignall transgression model and Isozaki's model focus on marine extinction. Th
Hallam and Wignall model requires a tight connection betwee
the appearance of geological indicators of low-oxygen waters an
the extinction, with the extinction occurring progressively as se
level rises. In Isozaki's deep ocean anoxia model, the actual mod
of extinction is poorly articulated, but is evidently associated wit
the spread of the stagnant oceans. This model would be falsifie
if the extinction occurred on a different time scale than the anoxia, or if diverse faunas occurred in shallow waters at the sam
time as the super-anoxia was present in the deep oceans.

The oceanic overturn model of Andy Knoll and colleagues involves two partially independent hypotheses; each must be teste separately. First, the differences in extinction and survival should reflect species differences in ability to withstand high levels of carbon dioxide. Second, in their model carbon dioxide was produced from a reservoir in the deep sea, where it had built up over millions of years. Glaciation induced more vigorous circulation (the opposite of the claims of Isozaki's model) and initiated the release of the carbon dioxide. But the increased levels of carbon dioxide could be from a different source, and thus falsifying the mechanism does not necessarily invalidate the model.

The *Murder on the Orient Express* hypothesis is the most difficult to test. We may discover, however, that we can eliminate a number of hypotheses, but are left with several that are equally consistent with the available data. If so, two questions arise: Is there data that geologists could collect that would allow us, in principle, to discriminate between these hypotheses? Is there some underlying single cause that could unite all this seemingly distinct data? Particularly if the answer to the second question is no, we would have to seriously entertain the idea of multiple causes, perhaps interacting in a complex fashion.

Discriminating between so many possible causes is far simpler than it appears. As we move through subsequent chapters, keep the following issues in mind: Was the extinction rapid, even catastrophic, or a slower, more drawn-out event? This will clearly distinguish between several proposals. How well do environmental and climatic events correlate with the episodes of extinction? This can help separate cause and effect. Do the patterns of extinction match those expected from various extinction scenarios, in particular in the anticipated involvement of marine and terrestrial realms?

The distribution of geological resources across the globe is highly uneven: oil in the Mideast, water in some areas and deserts in others, and Permo-Triassic boundary rocks in China. Rocks spanning the boundary are found in other places: among them Greenland, Pakistan, Iran, and northern Italy. But these sequences are so plentiful in south China that any search for the causes of the extinction must begin there.

CHAPTER 3

South China Interlude

Meishan, Zhejiang Province, China
October 2003

I am teetering precariously on a nubbin of rock halfway up the cliff of an abandoned phosphate mine. Out in the valley the red tile roofs of Meishan provide a vaguely Mediterranean air to the subtropical setting of south China. The morning rain and fog have lifted, and through the haze, out beyond the village and a small river, I can see piles of coal and the mine adits that deliver miners into the warren of tunnels deep below me. *Meishan* means coal mountain in Chinese, and thick deposits of coal lie several hundred meters under the surface, deposited by the Middle Permian peat swamps that once covered this area. The seas gradually rose after the peat was laid down, covering the deposits with lime muds of the later Permian.

Off to my right I can hear the chatter of the rest of our group, and the sounds of a hammer as someone collects samples. I turn back to the cliff, continuing in my inept imitation of a mountain goat. My feet are planted on the very end of the Permian, a foot-thick layer of limestone known to boundary aficionados as bed 24. The dark gray limestone is stained a rusty red at the top. A close look at the rock reveals fragments of brachiopod shells and other