CHAPTER 1

A TIME OF DYING

If you could travel back in time 260 million years, you would find our planet had an unfamiliar geography. Nearly all of the landmasses were united into a single, giant continent. This was Pangea, and it stretched from pole to pole. On the other side of the world you would find a vast ocean, even larger than the present Pacific, called Panthalassa. Plunging into the ocean you would see some vaguely familiar groups—including mollusks, corals, and fishes—present in abundance, but as you strolled around the land, everything would look entirely strange. Large, lumbering, reptile-like creatures with faces covered in blunt horns ruled the world, and they crashed and blundered their way through vegetation composed of giant fernlike trees and conifers.

Despite the strange and superficially primitive appearance of terrestrial life, it actually represented a spectacular evolutionary achievement. This was the middle of the Permian Period, and for the first time, animals and plants had spread throughout the land and away from the wet habitats around rivers and swamps. This was the result of innovations, such as reptilian eggs and conifer seeds, that meant many organisms could now survive on dry land. In contrast, there had been few recent changes in the oceans. The Middle Permian marine realm was rather like that of the Carboniferous Period, and it was not a great deal different from that of the Devonian

Period before that. But this business-as-usual story was about to change. The first mass extinction in 100 million years was shortly to strike. The dominant land animals would be wiped out along with many of the ocean's most common species. This was a disaster, and it was just the first of a series of six catastrophes spread over the next 80 million years and included the worst examples the world has ever experienced. By the end of this age of extinctions, life everywhere had changed profoundly. In the oceans, the entire food chain, from the smallest plankton to the largest predator, was totally transformed. It was the same story on land. Dinosaurs now ruled the roost while swift little mammals darted around their feet. With the singular exception of the mass extinction that removed the dinosaurs, 66 million years ago, life was never again to experience such traumas.

This book attempts to explain and understand this worst 80 million years in Earth's history, a time marked by two mass extinctions and four lesser crises. To put the Pangean trauma into context, it is important to note that five major mass extinctions have afflicted the course of life. Scientists define mass extinctions as geologically brief intervals when numerous species go extinct in a broad range of habitats, from the ocean floor to forests, and at all latitudes, from the equator the pole. A true mass extinction represents global devastation with no hiding place. The first of the "big five" occurred 444 million years ago, at the end of the Ordovician Period. It was a fascinating event, associated with a short but intense glaciation (making it the only mass extinction event to be clearly linked to a cooling phase), and I wish I had reason to write more about it here, but it is not relevant to our story. Number two on the mass extinction list happened 70 million years later, during the Late Devonian Period. This was a time of several closely spaced crises for both marine life and also for the newly evolved amphibians, which had just taken their first steps onto land. Again, it predates the formation of Pangea and so is outside the scope of this book. Next up on the mass extinction roster is the Permo-Triassic crisis, and this is very definitely within the remit of this book. The gap between this crisis and the next, at the end of the Triassic, was the shortest of all the intervals between catastrophes, only 50 million years. Life did not have long to recover, and in fact, the Triassic Period was beset by its own succession of crises.

The final crisis was only 65 million years ago, and it famously wiped out the dinosaurs and many other groups, including the lovely ammonites, whose coiled shells make such attractive fossils. This Cretaceous-Tertiary crisis, as it is known, has been famously linked with a giant meteorite impact in the Yucatan Peninsula in Mexico and also with volcanism in India. Discussion of this event, and the debates on the cause, is also mostly beyond the remit of this book, although it gets a mention in chapter 7 because it provides a useful comparison with the older extinctions described here.

This book therefore includes two of the big-five mass extinctions in Earth history (the end-Permian and the Triassic) and four other extinction events. In so doing, the book attempts to put the subsequent success story in context and aims to provide an understanding of why life has since become so much more resilient, or at least much less prone to catastrophes (the occasional meteorite impact excepted) in the most recent 180 million years.

The time of interest begins in the middle of the Permian Period, spans the entire Triassic, and finishes in the Early Jurassic (fig. 1.1). There is no overarching name for this interval; on the contrary, it straddles one of the major divides of geological time, that between the Paleozoic and Mesozoic Eras, which are generally treated separately in geological and paleontological textbooks. This is unfortunate because the Permo-Jurassic has many recurring themes and similarities, and when viewed

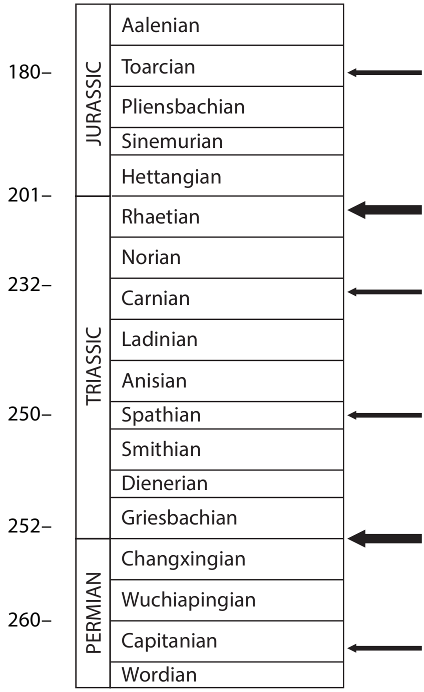

Figure 1.1. Subdivisions of geological time during the time of the Pangean supercontinent. The major extinctions are marked with arrows, and their age, in millions of years, is given to the left.

as a whole, it can be seen as a time when the Earth's oceans and climate showed distinctive and repetitive patterns. This is not to say that the interval is poorly studied. It includes the greatest disaster of all time, the Permo-Triassic mass extinction, 252 million years ago, which has been the subject of many academic papers and a substantial number of popular science books. The attention is merited because it was the world's worst ordeal. Its cause is one of the great topical debates in science. However, setting this mass extinction in its temporal context and comparing it with the lesser-known extinction events can help explain its origins and dispel any notion that it was a unique crisis. In fact, it was just the greatest of series of extinctions that had two factors in common: they occurred when the world's continents were united into the single continent of Pangea, and they coincided with gigantic volcanic eruptions. This book examines why volcanism at the time of a supercontinent is so bad for life.

Besides the great Permo-Triassic mass extinction, there were five other crises between 260 and 180 million years ago. Geologists only discovered some of these in the past few years, and so we are at an exciting stage with much to learn about them. The first extinction in the lifetime of Pangea, in the middle of the Permian Period, is generally known as the Capitanian extinction, being named after the geological interval in which it occurred. (Figure 1.1 lists the various time subdivisions used by geologists.) The crisis had a clear effect on tropical marine life, and it may have been devastating on land as well, as will be shown in chapter 2. There was only an 8-million-year recovery period from the Capitanian extinction before the devastating Permo-Triassic mass extinction struck. This caused entire ecosystems to disappear—it produced a world without forests and oceans without reefs. Vast swathes of the world were left devoid of life. The painfully slow recovery that followed in the first 5 million years of the Triassic was long regarded as a consequence of the sheer scale of the preceding blow. However, the latest research shows that there was probably another environmental calamity only a few million years after the Permo-Triassic mass extinction that knocked life back again before it had even begun to get back on its feet; this was the Smithian/Spathian crisis.

Only after the Early Triassic do we see a prolonged phase of diversification lasting more than 10 million years, the most peaceful interval of Pangea's history. This takes us to the Carnian Stage of the Triassic, when enigmatic and strange climatic change coincided with remarkable and equally puzzling changes among plants and animals. We are only just beginning to unravel the story of this time, let alone understand it.

Next up was the end-Triassic mass extinction, 202 million years ago. Once again huge changes were wrought on communities on both land and sea, with perhaps the most consequential being an emptying of the terrestrial landscape that allowed a formerly insignificant group called the dinosaurs to take center stage. This extinction marked the start of nearly 140 million years of almost trouble-free, dinosaur-dominated history. Or did it? Well, not quite. Within 20 million years of the start of the Jurassic, during the Toarcian Stage, a final extinction struck. It had many of the hallmarks of earlier Pangean crises, albeit with a much more muted expression. Its effects are best seen among marine life, whereas it is not clear if the dinosaurs (or anything else on land) were in any way bothered at this time.

After the Toarcian, Pangea began to split up and life thrived once again. The vicissitudes of times past were forgotten until one fateful day 66 million years ago, when a large meteorite struck the Yucatan Peninsula in Mexico. So, did life become tougher and less extinction-prone during the Jurassic, or did it just get luckier, with fewer environmental disasters? To answer this question we need to understand first how the Pangean extinctions were caused and then we need to know if these conditions were replicated latter.

The story of the worst 80 million years and its coincidence with Pangea also requires us to be familiar with the geological history of this supercontinent. Its assembly began before the Permian, when a large, southern hemisphere continent, called Gondwana, collided with a large, northern continent, called Laurasia, around 300 million years ago. The result was a larger continent (Pangea) with a mountain range, called the Central Pangean Mountains, along the suture that ran roughly

Figure 1.2. World map during the Permian Period, 260 million years ago, showing that most continents were united into the single supercontinent called Pangea. The other side of the world was single giant ocean called Panthalassa. Outlines of the modern continents are faintly shown.

east to west through the equatorial heartland (fig. 1.2). The worn-down segments of this range have now been split up, as a result of the formation of the Atlantic Ocean, but they can still be seen in the United States (the Allegheny Mountains), Morocco (the Anti-Atlas Mountains), and Spain, where they are impressive but not on the scale of the Himalayas.

Following the Gondwana/Laurasia collision, the final major pieces of the Pangean jigsaw—the continents of eastern Siberia and Kazakhstan—were the next to collide in the Early Permian and they formed the Ural Mountains. The final result of all this multicontinental pileup was a vast, arcuate supercontinent that by Middle Permian times, 260 million years ago, stretched from the North to the South Pole. The northern and southern arms of Pangea formed the shores of a large equatorial ocean called Tethys, while the other side of the world was entirely the truly vast Panthalassa Ocean. However, Pangea had not quite gobbled up all the world's continents: the eastern end of Tethys was partially blocked with several small continents that are today to be found in southeastern Asia. It is in the nature of small continents that they tend to be low-lying and so are commonly inundated by the sea. South China was one of these small continents, and thanks to persistent marine flooding, its marine sedimentary rocks provide an excellent record of life in the oceans.

No sooner had Pangea assembled than it started to fray at the edges as small continental slithers broke away from the Gondwanan margin and drifted northward through the Tethyan Ocean. By the end of the Triassic, 200 million years ago, these fragments (which included parts of present-day Iran, Turkey, and Tibet) had collided with northern Pangea. At the same time, the continents of North China and South China had similarly glued themselves to the northern Tethyan margin. The end result was a truly unified supercontinent that had its brief apogee in the Early Jurassic. However, continental drift is a ceaseless process, and fragmentation began immediately after the assembly. The first rupture began in the equatorial heart of Pangea, where Africa and the Americas were joined, and it spread southward as the Atlantic gradually "unzipped."

The mere existence of Pangea alone was not enough to create hostile conditions; indeed, for most of the continent's duration, life was constantly diversifying, and as we shall see, many new groups evolved, including the dinosaurs, mammals, and flowering plants. The key factor in the six crises of Pangea was volcanism. This was not the normal, everyday-type volcanic activity that produces volcanoes; rather, it was the most voluminous style of eruption ever recorded. Every Pangean extinction event coincided with the outpouring of enormous fields of lava called flood basalt provinces. The lavas were very low viscosity and flowed for hundreds of kilometers, infilling valleys and hollows in the land surface with a sea of magma. Successive flows stacked up in a series of thick layers that gradually weathered to form a staircase-like topography that is often called "traps," named after the Dutch word for "stairs" (and in English we have trapdoors that lead to staircases). Geologists also call these volcanic regions large igneous provinces, which allows them to use the acronym LIPs and thereby give semi-amusing titles to conference talks, such as "LIPs—The Kiss of Death" and "Beware of Big, Wet LIPs" and . . . anyway, you get the idea.

It is probably fortunate that there is no volcanism today that approaches the scale of LIP volcanism. Each province typically includes at least a million cubic kilometers of lava composed of hundreds of individual flows, each with volumes of several hundred to several thousand cubic kilometers. No eruption in historical time has come anywhere close to being so large. For comparison, the Mount Pinatubo eruption of 1991, the biggest eruption of the twentieth century, involved only 5 cubic kilometers of magma, and even the Tambora eruption of 1815, probably the largest eruption of the past millennium, erupted only 30 cubic kilometers of magma. Clearly LIPs provide a very big "smoking gun" to explain Pangean mass extinctions, but explaining just how the volcanic "bullet" did the killing is far from understood. Making the connection between volcanism and catastrophe is made even more difficult by the fact that although the relationship

Pangea + LIP volcanism = mass extinction

holds true, once Pangea is removed from the equation, the link fails. By Cretaceous times (145–66 million years ago), Pangea had long since broken apart, and the LIPs that erupted in this period did not cause major extinctions. Only the final LIP of the Cretaceous, the Deccan Traps of India, coincided with the famous death of the dinosaurs. But of course this crisis also coincided with a meteorite impact in Mexico, thereby vastly complicating all cause-and-effect scenarios. Further LIP eruptions have occurred within the past 65 million years, including a truly enormous example now found along the margins of the North Atlantic, but their consequences were fairly insignificant.

The task of this book is therefore to examine what happened during the Permo-Jurassic extinctions of Pangea, evaluate what may have caused these catastrophes (more specifically, to ask, how volcanism could have done it?), and finally to understand whether the resilience of the biosphere has changed in 260 million years or whether it has just become luckier thanks to continental separation; in other words, are supercontinents bad for life?

An incidental bonus of working on past environmental disasters is that giant volcanism produces effects that may be akin to modern anthropogenic activity, such as the emission of huge amounts of carbon dioxide into the atmosphere. The relevance of understanding ancient "violent shocks" when it comes to predicting near-future worlds has not been lost on geologists, not least for the prosaic reason that it provides a justification for research funding.

Until recently, most modern extinctions could be attributed to overhunting or habitat destruction. One need only think of the iconic dodo or the numerous bird species that were lost from Hawaii as the forests were destroyed and exotic animals introduced. However, the past decade has witnessed rapidly growing concerns over the effects of global warming and climate change. The rapid shift of climate belts may prove too fast for species to migrate, especially in fragmented landscapes, where only small islands of original habitat survive in a "sea" of agricultural land. In the oceans, warming will cause acidification by carbon dioxide and a decline in dissolved oxygen. Both factors are major contenders, albeit contentious ones, in marine extinction hypotheses for the Pangean crises. The debate on what caused the Pangean extinctions is therefore of relevance to the attempts to predict how life will survive in the coming centuries, although I do not intend to overstress this latter aspect. This is primarily a book about a time when Earth was very different, a time of supercontinents, super-oceans, and super-eruptions, and above all, an age of mass extinctions.