CHAPTER ONE

No Vestige of a Beginning . . .

> If nobody asks me, I know what time is, but if I am asked, then I am at a loss what to say.
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> Saint Augustine of Hippo, A.D. 354–430

While hiking in the Alps one day in 1991, Helmut Simon and his wife had a disturbing experience: they discovered a body. It was partly encased in the ice of a glacier, and their first thought was that it was an unfortunate climber who had met with an accident, or had been trapped in a storm and frozen to death. Word of the corpse spread quickly, and a few days later several other mountaineers viewed it (see figure 1). It was still half frozen in the ice, but they noticed it was emaciated and leathery, and lacking any climbing equipment. They thought it might be hundreds of years old. This possibility generated considerable excitement, and in short order the entire body was excavated from its icy tomb and whisked away by helicopter to the Institute of Forensic Medicine at the University of Innsbruck, in Austria. Researchers there concluded that the corpse was thousands rather than hundreds of years old. They based their estimate on the artifacts that had been found near the body.

As careful as the Innsbruck researchers were, their age assignment for the ancient Alpine Iceman—later named Oetzi after the mountain

Figure 1. Oetzi, the Alpine Iceman, still partly frozen in ice shortly after his discovery. Two mountaineers, Hans Kammerlander *(left)* and Reinhold Messner *(right)* look on, one of them (Kammerlander) holding a wooden implement probably used by Oetzi for support. Photograph by Paul Hanny / Gamma, Camera Press, London.

range where he was found—was necessarily qualitative. An ax found with the body was in the style of those in use about 4,000 years ago, which suggested a time frame for Oetzi's life. Other implements associated with the remains were consistent with this estimate. But how could researchers be sure? How is it possible to measure the distant past, far beyond the time scales of human memory and written records? The answer, in the case of Oetzi and many other archaeological finds, was through radiocarbon dating, using the naturally occurring radioactive isotope of carbon, carbon-14. (Isotopes and radioactivity will be dealt with in more detail in chapter 2, but, briefly, atoms of most chemical exist in more than one form, differing only in weight. These different forms are referred to as isotopes, and some—but by no means all—are radioactive.)

Tiny samples of bone and tissue were taken from Oetzi's corpse and analyzed for their carbon-14 content independently at two laboratories, one in Oxford, England, and the other in Zurich. The results were the same: Oetzi had lived and died between 5,200 and 5,300 years ago (the wear on his teeth suggested that he was in his early forties when he met his end, high in the Alps, but that's another chronology story . . .). Suddenly the Alpine Iceman became an international celebrity, his picture splashed across newspapers and magazines around the world. Speculation about how he had died was rife. Did he simply lie down in exhaustion to rest, never to get up again, or was he set upon by ancient highwaymen intent on robbing him? (The most recent research indicates that the latter is most likely; Oetzi apparently bled to death after being wounded by an arrow.) Fascination about the life of this fellow human being, and his preservation over the millennia entombed in ice, stirred the imagination of nearly everyone who heard his story.

Oetzi also generated a minor (or perhaps, if you care deeply about such things, not so minor) controversy. When he tramped through the Alps 5,000 years ago, there were no formal borders. Tribes may have staked out claims to their local regions, but the boundaries were fluid. In the twentieth century, however, it was important to determine just where Oetzi was found. To whom did he actually belong? Although he was kept initially in Innsbruck, careful surveys of his discovery site showed that it was ninety-two meters (about one hundred yards), from the Austria-Italy border—but on the Italian side. As a result, in 1998 Oetzi was transferred (amicably enough) to a new museum in Bolzano, Italy, where he can now be visited, carefully stored under glacierlike conditions.

Radiocarbon dating is just one of several clever techniques that have been developed to measure the age of things from the distant past. As it happens, this particular method only scratches the surface of the Earth's very long history; to probe more deeply requires other dating techniques. But a plethora of such methods now exist, capable of working out the timing of things that happened thousands or millions or even billions of years ago with a high degree of accuracy. The knowledge that has flowed from applications of these dating methods is nothing short of astounding, and it cuts across an array of disciplines. For biologists and paleontologists, it has informed ideas about evolution. For archaeologists, it has provided time scales for the development of cultures and civilizations. And it has given geologists a comprehensive chronology of our planet's history.

The popular author John McPhee, who has written several books about geology, first coined the phrase "deep time." He was referring to that vast stretch of time long before recorded history and far beyond the past 50,000 years or so that can be dated accurately using radiocarbon. But even though McPhee's phrase is a recent invention, the concept of deep time is not. Without a doubt, it is geology's greatest contribution to human understanding. The idea that geological time stretches almost unimaginably into the past secured its first serious foothold in the eighteenth century, when a few brave souls, on the basis of their close observations of nature, began to question the wisdom of the day about the Earth's age, which was then strongly influenced by a literal reading of the Bible. Today, deep time—and also the "shallow time" of the more recent past—is calibrated by dating methods based on radioactivity. These techniques provide the accepted framework for understanding the history of the universe, the solar system, the Earth, and the evolution of our own species. Without the ability to measure distant time accurately, we would be without a yardstick to assess that history and the many basic natural processes that have shaped it.

For as long as we have written records, there are frequent references to time and its measurement. These have been persistent themes not only for scholars and philosophers, but also for those of a more practical bent. From the earliest times, the sun, moon, and stars were used to mark out days, months, and years—to govern agricultural practice and to formulate rough calendars. Wise men and priests of every culture used an understanding of astronomy to predict the time of a solstice or an eclipse, and sometimes they gained great power and influence from this apparently magical skill. By the time of the Greeks, sophisticated instruments were being produced that accurately traced out solar years, lunar months and the phases of the moon, eclipses, and even the movements of the visible planets.

The technical prowess of the Greek craftsmen who made these instruments is hinted at in written accounts from the time but was only truly realized through an accidental discovery in 1900, when a sponge diver came across an ancient shipwreck near the tiny Greek island of Antikythera. He didn't linger at the site of his discovery because the wreck was disconcertingly littered with bodies. However, later divers found that it was also full of works of art. And among the bronze and marble sculptures from the ship that were eventually assembled at the National Museum in Athens was a nondescript chunk of barnacle-encrusted bronze, partially enclosed in a wooden box. This initially overlooked artifact turned out to be one of the most ingenious and complicated time-telling devices ever constructed; it has even been called the world's first computer. The "Antikythera mechanism," as it is now known, is thought to have been made between 150 and 100 B.C. It comprises more than thirty interconnected and precisely engineered geared wheels that work together as an astronomical calendar. Prior to its discovery, this kind of technology was not thought to have been widely used until about the fourteenth century. It is a marvel of Greek intellectual achievement, and must have been highly valued for the knowledge it imparted about time and the universe. Nothing quite like it appeared for another thousand years or more.

Long before the development of the Antikythera mechanism, however, time, especially as it relates to the history of the world, was an important component of religious beliefs. Early Hindu texts describe multiple cycles of creation and destruction of our world, each lasting 4.32

billion years, which, according to these sources, is just one day in the life of Brahma the Creator. By weird coincidence, that number is quite close to today's most precise measure of the Earth's age. But Brahma's nights are just as long as his days, doubling this number to 8.64 billion years. And each Brahma (there are endless cycles of them) lives for one hundred years, so the age of our world quickly becomes unimaginably large according to this system. Regardless of the exact value, however, it is clear that Hindus are used to thinking about truly deep time—time on a vast scale.

Christians, too, developed a time scale for the Earth, theirs based on the Old Testament of the Bible and exceedingly short compared with that of the Hindus. The best known is the monumental work (over two thousand pages long) by the Irish archbishop James Ussher, published in 1650. Although his conclusion—that the Earth was created on the evening of October 22 in 4004 B.C.—is now often the butt of jokes, Ussher was a serious scholar following in the footsteps of many others who had, over the centuries, tried to piece together a history of mankind based on the Bible. (Ussher's date for the creation of the Earth is usually given as October 23, and it is often said, erroneously, that he stipulated the beginning of the working day, 9 A.M., as the start of it all. But in Ussher's conception of the world's beginning, God wasn't quite so precise. What Ussher actually wrote was, "[The] beginning of time, according to our chronology, fell upon the entrance of the night preceding the twenty-third day of October in the year of the Julian calendar 710." Sometimes "entrance of the night" is taken to mean midnight. So whether Ussher really meant October 22 or October 23 is a matter of interpretation.)

Ussher and his scholarly predecessors believed that the Old Testament provided most of the information they needed to document the entire history of the Earth. This was, at the time, not an unreasonable assumption as there were no other data available to calibrate the world's time scale. Adam was created five days after the Earth was made and was 130 years old when his son, Seth, was born; Seth himself had a son when he was 105; and so on. By adding up lifespans, and making some educated guesses about times when there were gaps, these Old Testament scholars thought they could determine pretty accurately when God created the Earth. Ussher's work was the culmination of this kind of calculation, and it held sway for a very long time; for more than two centuries after his book was published, most Bibles were printed with Ussher's dates displayed prominently in the margins throughout the Old Testament.

But as Ussher worked on his Bible-based time scale for the world, the Enlightenment—the so-called Age of Reason—was dawning in Europe. Although initially closely allied with Christian religious ideals, the Enlightenment inevitably led to the modern scientific approach encompassing observation, experimentation, and hypothesis testing of the physical world, and to a much more secular view of nature. Into this milieu stepped a man whose contributions to our understanding of time are often unappreciated, except perhaps among geologists: James Hutton.

Hutton was born in Edinburgh, Scotland, in 1726, and in his prime he was one of a circle of intellectuals that gave the city its nickname Athens of the North (a much more attractive title than its other nickname, Auld Reekie, which apparently referred either to the foul smell of sewage thrown out of tenement buildings into the narrow streets below, or to the sooty smoke of its coal and wood fires, or maybe even to both). The Edinburgh intellectuals included men such as Adam Smith, James Watt, and David Hume, all of whose work had worldwide impact. Hutton's ideas were equally groundbreaking, although his name is far less widely known today than those of his famous compatriots. He was a global thinker, and he set out to develop a coherent explanation for natural processes on the Earth in the same way that Newton had done before him for the movements of the planets.

For part of his life, Hutton was a gentleman farmer. That experience was crucial for his thinking about the time scales of natural processes, because he observed that the soil on his farm formed—very, very slowly—by erosion of the underlying rocks. He also noted that some of the eroded material was washed into rivers and carried to the sea, where it was deposited as layer after layer of mud and silt and sand. Over long periods of time, through processes that he didn't entirely understand, the buried sedimentary layers hardened into solid rocks. But not all these sedimentary rocks remained on the sea floor. They were found commonly on land, too; in fact, many of the buildings in his native Edinburgh were constructed from blocks of sedimentary sandstone cut out of local quarries. How did they get there? Hutton's solution was that deep burial of the ever-accumulating sediments created heat, often to the point of melting, and when that happened, the whole mass expanded and was thrust up out of the sea to form the hills and mountains of dry land.

Hutton was a creative thinker, but he was also a product of his time. It was the beginning of the industrial revolution, and machines were beginning to take over mechanical tasks. Hutton's view was that the workings of the Earth were not very different from the operations of a machine or an industrial process. (The modern view is similar. What used to be called "geology" is now often referred to as "earth system science," a title meant to emphasize the integrated behavior of Earth processes.) Hutton envisioned an Earth progressing through a natural cycle: erosion of the land, deposition of sedimentary layers in the sea, solidification, heating, and uplift. But history didn't begin or end there; this cycle could be repeated ad infinitum, each step automatically requiring that the next follow. And all the geological processes in these cycles, Hutton understood, took place extremely slowly by human standards. It would require unimaginably long periods of time to erode a landscape, build up thick accumulations of mud and sand, harden them into sedimentary rocks, and finally raise them up out of the sea to where they now stand in the countryside. If such cycles occur over and over again, it would mean that today's landscape is the result of only the most recent cycle. The unimaginably long duration of a single cycle would have to be multiplied many times over to explain the whole of the Earth's history.

Most accounts of Hutton's work assume it was stimulated by direct observation. It is difficult to imagine that his ideas might actually owe more to philosophy than to observation—specifically the philosophy, common in Hutton's time, that nature operates in an unchanging way for the benefit of man and the animal world (the production of fertile soil through processes of erosion being one example). Yet that is what Stephen J. Gould argues in his book *Time's Arrow, Time's Cycle,* noting that Hutton visited several now-famous "Hutton localities" only *after* he had worked out his theory for the Earth. Still, even if he used observations simply to bolster his already-developed theories, it is clear that Hutton was an astute observer. He was among the first to challenge the then-popular idea that granite is produced by precipitation from the sea. Instead, Hutton suggested, it is formed by cooling from a molten state (as we now know to be the case for granite and all other igneous rocks). This idea was based on localities where Hutton observed igneous rocks that demonstrably intruded, liquidlike, into preexisting sedimentary rocks. The reality of such processes neatly fit his theory of burial, heating, and uplift, and it emphasized the very long periods of time necessary for all these processes to operate. One of the places Hutton observed this phenomenon was not far from his home in Edinburgh. Today the site is a mecca for visiting geologists. It can be found easily, just a stone's throw from the Scottish Parliament buildings, on a hillside in the royal estate that is now an enormous park within the city of Edinburgh.

Hutton also recognized that the features geologists refer to as unconformities, which are preserved ancient erosion surfaces, constituted strong evidence that his theory was correct. A sketch drawn by his friend John Clerk (another of the Edinburgh intellectuals, Clerk wrote a classic book on naval warfare and was eventually knighted) shows one of the unconformities Hutton visited near the Scottish town of Jedburgh (see figure 2). The wealth of information contained in this simple image is quite amazing. To the casual observer, it looks like a pretty sketch of a rock outcropping in the countryside, but to Hutton the rock layers told a long and complicated story. It was not as though no other geologists had been to this locality; many had. But Hutton viewed it with fresh eyes, and saw that this one outcrop validated most

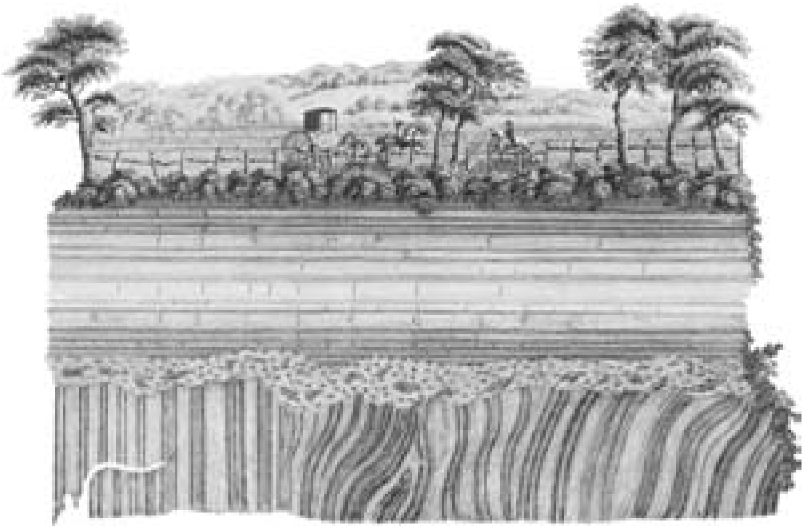

Figure 2. A somewhat idealized sketch of an unconformity observed by Hutton near Jedburgh, Scotland. This sketch, drawn by Hutton's friend John Clerk, appeared in volume 1 of Hutton's *Theory of the Earth, with Proofs and Illustrations,* published in 1795. The sequence of sedimentary layers in this simple drawing illustrates dramatically Hutton's ideas about repeated natural cycles.

of the ideas in his theory. Geology, the evidence in front of him said, is not simply a process of erosion and decay, as some of his compatriots thought. Rather, it involves cycles and includes renewal.

In Clerk's sketch, the lowest band of rock strata stands almost vertical. But because these are sedimentary layers, Hutton knew that originally they had been laid down horizontally in the sea, the accumulated products of erosion of the land, and then buried and hardened into solid rock. Deep burial heated the rocks, and heating led to uplift. Somehow, these once-horizontal rocks had been tilted upright and thrust onto the land. Once out of the protective sea, wind and rain began to take their toll, and erosion produced the slightly undulating surface that can be seen cutting across the upturned strata. This is the actual unconformity, the ancient erosion surface. Note that a layer of loose rubble—unconsolidated erosion products—lies atop the unconformity. Hutton's entire natural cycle can be inferred from just this one sequence of rocks. But other sedimentary layers lie above the unconformity, these ones horizontal. Their presence requires that the land was once more submerged, sediments again deposited and hardened into rock, and then uplifted (or perhaps the sea retreated), leaving the entire succession once more on dry land. Present-day erosion has formed a layer of soil across the uppermost sedimentary strata. Clerk depicted several human travelers crossing the landscape, presumably blissfully unaware of the great geological story that lay just beneath their horses' hooves.

Hutton's conclusion that the repeated geological cycles required great stretches of time to operate was his most important contribution to science. Given the prevailing view, even among some scientists, that the Earth was only 6,000 years old, this was a radical idea. There were many critics, and, among other things, Hutton was called an atheist, a slander that in those days was a serious and hurtful charge. Even among those interested in geology and the Earth's history, his ideas were not rapidly accepted; they gained widespread prominence only after they had been popularized by others. Part of the reason was Hutton's writing. While it may have been appreciated by his small circle of fellow intellectuals, it was almost impenetrable to many others, guaranteed to frustrate or put them to sleep. But there is one place where Hutton got it just right. In 1788, in a long paper titled grandly *Theory of the Earth,* he summed up his thoughts about geological time: "The result, therefore, of our present enquiry is, that we find no vestige of a beginning, no prospect of an end." That short phrase—"no vestige of a beginning, no prospect of an end"—has endured; it is as powerful as any that has been written since and is one of the most frequently quoted in all geology.

Hutton's ideas about the immensity of geological time shook up the eighteenth-century world of science and natural philosophy, and the theological world, too. But Hutton did not quantify his results—indeed, at the time he had no way to do so. He didn't know whether the slow geological processes he observed had been going on for a million years, 100 million years, or even longer. His approach was essentially and necessarily qualitative; the task of working out how to measure the time scales of the Earth's operation would have to be carried out by others.

Although it is convenient to treat scientific breakthroughs as singular events, it is rare that they really are so. Hutton is clearly the person who should be credited with establishing the immense sweep of geological time—he was, after all, the first to map out the connections between slow, ongoing processes and the creation of the landscape around us. But there had been earlier rumblings, based on different criteria, that had also suggested a much longer history for the Earth than allowed by the biblical scholars. Even Newton got into the act. He was doing experiments on the rate at which hot objects cool down, and, after determining that a one-inch iron sphere would cool from red heat to room temperature in about an hour, he extrapolated to a sphere the size of the Earth. His calculations indicated that more than 50,000 years would be required. The consensus among Newton's contemporaries was that the Earth had begun its life as a molten globe, and, if this was so, his 50,000-year cooling time would be a rough approximation of its age. Newton never claimed to have determined the Earth's age, but his results were well known among scientists of the time. However, although his estimate was almost a factor of ten greater than Bishop Ussher's 6,000 years, it was still too short to accommodate Hutton's cycles.

More than a century after Newton's experiments, several other researchers used this same approach in explicit attempts to estimate just how old the Earth is. The most famous calculations were done by William Thompson, who was the professor of natural philosophy at Glasgow University for over fifty years, from 1845 until 1899. (Thompson is better known today as Lord Kelvin, a title bestowed on him when he was made a baron in 1892. To avoid confusion, that is how I will refer to him in what follows.) By the time Lord Kelvin did his work on the Earth's age, Hutton's ideas were well entrenched in the geological literature. But Kelvin was a physicist, and he had a physicist's distain for what he saw as the intuitive and qualitative methods that had been used by Hutton and other geologists. He claimed that Hutton's analysis of the problem was flawed. If the Earth had initially been very hot, or perhaps even molten, he argued, the geological processes in that much hotter past would have been quite different from those we observe today. Hutton had assumed that he could simply extrapolate present-day rates into the very distant past; that, said Kelvin, was wrong.

Why did Lord Kelvin and other physicists think the infant Earth had been very hot? Their main evidence came from observations in deep mines. It was well known that the temperature increases as one descends deeper and deeper into a mine. To a physicist, the existence of such a gradient meant only one thing: our planet is cooling. Heat flowing from a hot interior to the cooler surface produces the observed temperature gradient. This implied a hotter Earth in the past, although just how hot was a matter of conjecture.

Kelvin made some assumptions about the Earth's initial temperature, and about how the process of cooling would proceed, and then calculated how long it would take to reach its present state. He announced his results in 1862: the most probable age for the Earth, he said, was 98 million years. He added a caveat, however. Because of uncertainties in his data and the assumptions he had to make, the actual formation time could lie anywhere between 20 and 400 million years ago.

Lord Kelvin was an influential figure in nineteenth-century Britain, and any results he published were taken very seriously. In addition to his purely scientific work, he was involved in the laying of the first trans-Atlantic cable, and he invented a receiver for the submarine telegraph. Queen Victoria knighted him for his services to science and the country, and the Kelvin temperature scale is named after him. But in spite of his fame, and in spite of the fact that many geologists were chastened by the apparently unimpeachable quantitative approach of this powerful man, there was a lot of unease about his age for the Earth. To some of those who were actively involved in fieldwork and familiar with the everyday processes shaping the landscape, even 98 million years didn't seem to be enough time into which to fit all observable geology.

There was also concern about the very large uncertainty in Lord Kelvin's result—after all, the difference between 20 and 400 million years is huge, a factor of twenty. As a consequence, other scientists, notably a man named Clarence King in the United States, set out to refine the calculations. King accepted Lord Kelvin's assertion that the age of the Earth could be determined by calculating how long it took to cool. However, he also understood that the result of the calculation would only be as good as the data that went into it. It took the invention of the computer to popularize the phrase "garbage in, garbage out," but King understood the principle very well. He knew Kelvin's data on the thermal properties of earth materials—how they held and conducted heat—were not very good, so he set about to improve the situation. He conducted experiments on the melting temperatures of different kinds of rocks, and then extrapolated his data to the high-pressure conditions that prevail in the Earth's interior. With this new information he redid the cooling calculations and concluded that it would have taken just 24 million years for the planet to reach its current state. This was much less than Lord Kelvin's "most probable" age of 98 million years, but it was still within the range he had proposed, albeit near the low end.

Kelvin was pleased because the new result did not contradict his calculations, and he subsequently incorporated King's data into a revision of his own earlier work. By the late1890s, Kelvin had significantly reduced his allowed range for the Earth's age. It must lie between 20 and 40 million years, he announced, and is most likely closer to 20 than to 40 million. Such was Kelvin's influence that the 20-million-year figure became the accepted wisdom about our planet's age among most scientists. However, this new value caused even more unease among geologists. Not only did they have to fit Hutton's repeated, slow geological cycles into this time span, but now they also had to accommodate the entire course of biological evolution as championed by Charles Darwin.

Lord Kelvin's earlier estimate of 98 million years was already a squeeze; 20 million years did not seem nearly long enough.

Lord Kelvin and Clarence King were by no means the only nineteenth-century scientists to turn their attention to the Earth's age. Nor was the cooling-sphere model the only approach to the problem; many other ingenious ideas were also proposed. Among them was one by George Darwin, the son of Charles and a distinguished scientist in his own right. Darwin assumed that in the beginning the Earth was rotating very rapidly—so rapidly, in fact, that the moon was literally thrown out from the Earth. It was already known in Darwin's day that the Earth's rotation rate is slowly but inexorably decreasing because of tidal friction caused by the moon (and because of this the moon is gradually moving farther away from the Earth). So Darwin calculated how long it would take for the rotation rate to slow to its present value, and came up with an answer of 50 to 60 million years. This, he thought, was a plausible age for the Earth. However, he hedged a bit by saying he couldn't be sure the moon actually formed in this way. If it didn't, it was possible that the Earth was much older.

A completely different but equally imaginative tack was taken by John Joly, an Irish geologist, who made estimates based on the amount of salt in the sea. The source of the salt, Joly knew, is rivers, which continuously carry large amounts of dissolved materials from the continents to the sea. If this process had been going on since the Earth formed, the sea must be getting progressively saltier. Joly reckoned he could calculate the Earth's age simply by dividing the amount of salt in the ocean by the rate at which it is supplied by rivers (he used the sodium content for his calculations; ordinary sea salt is sodium chloride). That sounds straightforward, but Joly, like Clarence King, knew that the result would only be as good as the data used in his calculations. It would obviously be impossible for him to measure the salt content of every river in the world. However, in the best tradition of science, he made reasonable assumptions where he didn't have hard data. His calculations indicated that the Earth is about 90 million years old.

Some geologists tried to determine the Earth's age using an approach that was similar to Joly's, except that they substituted sediments for sodium. But their approach was even more problematic. These scientists had to estimate the total volume of sedimentary rocks that had accumulated over the whole of the Earth's history, and then divide this number by the amount of sediments being formed annually today. Accurately measuring or estimating these quantities was very difficult, and the exercise involved multiple assumptions. Nevertheless, several such calculations were published, and they typically gave ages in the range of 50 to 100 million years. Still, even most of those who had a stake in this work admitted that there were huge uncertainties. And if Hutton was right about recycling, the sediments accumulating today were likely to have been eroded from previously existing sedimentary rock. If this were true, the calculations would substantially underestimate the Earth's age.

In spite of all the caveats, real numbers published in scientific papers are seductive things, and the ages calculated by Clarence King, Lord Kelvin, John Joly, George Darwin, and the geologists tallying up sediment volumes all had their supporters in the scientific community. None of these calculations produced ages greater than about 100 million years, and they ranged down to just 20 million years. These values influenced even geologists who adhered to Hutton's (qualitative) theory of a very ancient Earth. The general consensus was that our planet must be, at most, no more than a few hundred million years old.

Among the early calculations, the estimates made by Clarence King and Lord Kelvin—which gave the youngest values for the Earth's age—seemed to many of their fellow scientists to be the most reliable, because they were based solidly on well-known physical principles. If the Earth had once been hot, and was slowly cooling down, it seemed inescapable that Lord Kelvin's calculations were basically correct. And, indeed, his science was faultless—as far as it went. But neither Kelvin nor anyone else knew then that there are two other natural phenomena that should have been taken into account; their omission made Kelvin's age of the Earth grossly inaccurate. The more important of these phenomena is convection in the Earth's interior, which actively moves hot material toward the surface and cool material to deeper levels. This produces quite a different temperature gradient near the surface than would occur in the rigid Earth that Kelvin assumed for his cooling calculation. The second phenomenon is radioactivity. Small quantities of naturally occurring radioactive isotopes dispersed throughout the Earth's interior produce heat as they decay, and because of this the overall rate of cooling is reduced. In an ironic twist, this same process would, much later, become the basis for our present-day understanding of the Earth's true age.

Radioactivity was discovered very near the end of the nineteenth century. Within less than a decade, several perceptive scientists had realized that it might be a tool for measuring deep time, and a few initial attempts were made to determine the age of rocks that geologists had, up to that time, described only as "very old." The early measurements were rudimentary, but they implied that some of these samples were as old as half a billion years. This was a revolutionary finding—if it were to prove correct, it would mean that the Earth was really many times older than any of the estimates by previous workers had suggested. As you can imagine, there were many skeptics. Supporters of Lord Kelvin simply couldn't comprehend how the great man's calculations could be so badly wrong. Others were so strongly influenced by the entrenched idea that the Earth was no more than about 100 million years old that they simply could not imagine a much older planet. But gradually, as the phenomenon of radioactivity became better understood and more old rocks were dated, most scientists came to accept that the Earth really must be very ancient. There were a few holdouts who for a long time believed that there must be some flaw in the new dating techniques. But, by the middle of the twentieth century, these voices had been drowned out by the success of the approach. As older and older dates were reported, it really did seem that Hutton's "no vestige of a beginning" might be almost literally true.

Radioactivity often gets something of a bad rap; mention it to most people and they immediately think of the devastation at Hiroshima or the nuclear accidents at Three Mile Island or Chernobyl. And it is certainly true that high levels of radioactivity are very dangerous to human health, as was shown dramatically when a Russian ex-spy was mysteriously poisoned in London, England, in 2006. It turned out that the substance responsible for his horrifying and painful death was a radioactive isotope that most people have never heard of, polonium-210. But there is another side of the coin, too. All around us, in the air we breathe, in the water we drink, and in the ground we walk on, there are small amounts of natural radioactivity. In fact, polonium-210 is one of those isotopes, and there are very small amounts of it in your body and mine. In most places on Earth, the quantities of such isotopes are minute enough that their presence poses no danger. But their widespread occurrence is a huge boon for scientists, because it provides a whole array of natural clocks, ticking away in nearly every natural substance.

Dating objects from the distant past using the principles of radioactivity is today referred to as "radiometric dating," and, unlike earlier times, when most of those who did such work were physicists, there is now an entire subfield of the earth sciences devoted to geochronology, the science of measuring past time. Geochronologists may be chemists or geologists or physicists by training, but they have one overarching goal: the accurate measurement of time. Some are mostly interested in improving instrumentation, others in exploring in detail some particular slice of geological time. Together they have managed to find ways to use almost every radioactive isotope that exists in nature to measure the age of things—from the universe itself to archaeological artifacts only a few thousand years old. It has required a great deal of ingenuity and persistence to develop these methods, but the dating tools are now so well honed that they are taken for granted by almost everybody.

That "taking for granted" attitude was one of the primary reasons for writing this book. Most people don't think twice when they hear that archaeologists have found an artifact and dated it to 9,000 years, or that paleontologists have unearthed the fossil of a strange creature that lived 150 million years ago. They don't pause to wonder just how scientists arrive at such amazing conclusions. And when I quizzed friends and acquaintances—and some bright undergraduate students—about radiocarbon dating, it turned out that they had all heard of it, but, zbeyond that, their understanding was murky. Most of them didn't realize that radiocarbon dating is not useful for dating rocks, or that it is restricted to a very narrow, very recent portion of past time. As for other dating methods, well, for the most part they were completely ignorant. There is nothing inherently wrong with that—especially in this age of information overload, there are many parts of human knowledge that most of us are ignorant about. But it does seem to me that understanding time, especially how time in the distant past is measured and how our ideas about it have evolved and transformed, is crucial to understanding our own place on this planet Earth.

I have been fortunate enough to spend much of my career doing research in isotope geology and geochronology. For me, and, I dare say, for most scientists, there are few things in life more satisfying than the thrill that comes with discovery. Even if it is a very minor discovery in the overall scheme of things, there is nothing quite like realizing you are the first person to know what you have just found out. In this book I have tried to illuminate some such moments in the development of radiometric dating methods, and I hope they provide a sense of the excitement experienced by the scientists who did this work. Even if you are not personally involved, it is hard not to be inspired by the remarkable creativity and inventiveness of those responsible for working out ways to measure the age of almost every conceivable artifact and object from the far reaches of time.

But before I jump into a discussion of just how that is done, and what scientists have discovered using these techniques, I will provide in chapter 2 a brief introduction to radioactivity and how it was discovered, necessary background for understanding radiometric dating. In that chapter, as elsewhere, I have tried to avoid complex or technical discussions that are more suited to a textbook. However, for those who are interested, I have included additional material in appendix C that expands on some of these technical aspects. These short notes are certainly not meant to be comprehensive, but they do introduce aspects of radioactivity that are not covered in the main text and include details of the equations used to calculate ages for some of the dating methods described in the book.

After exploring radioactivity in chapter 2, I deal at some length with radiocarbon dating in chapters 3 and 4—how it came about, and what some of its important applications are. That, I think, is important, because, of all the dating methods that exist, it is the one most commonly in the public eye. It is also the only one that earned its inventor a Nobel Prize. And its development is a good example of how scientists work, and how one discovery leads to another. Furthermore, radiocarbon dating provides a good general introduction to how it is possible to determine the age of things using radioactivity.

Chapter 5 turns to the other end of the time scale and examines the quest to determine the Earth's age accurately using modern dating methods. Doing that was a singular feat, accomplished just over fifty years ago, and, in spite of many refinements in instruments and procedures since then, the result has been little improved upon. Chapters 6 and 7 focus (mostly) on the realm of deep time, exploring how radiometric dating has transformed the originally qualitative and relative geological time scale into an accurate chronology of the Earth's history, and how the progress of biological evolution has been charted through accurate age determinations. Chapter 8 returns again to radiocarbon dating, and examines some of its more interesting recent applications, including such things as working out the timing of earthquakes in the Pacific Northwest of the United States and dating the Shroud of Turin. In the final chapter I highlight some of the important advances in the field of geochronology, and show how these have led its practitioners into some fascinating new fields of research. For reference at the end of the book are a glossary, appendixes containing a current geological time scale and the periodic table of chemical elements, and a listing of books and articles for further reading.

If all these things whet your appetite to learn more about the Earth's history, this book will have accomplished its aim.