Nature's Clocks

How Scientists Measure the Age of Almost Everything

Doug Macdougall

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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.
>
> 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 elements 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 exists, 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

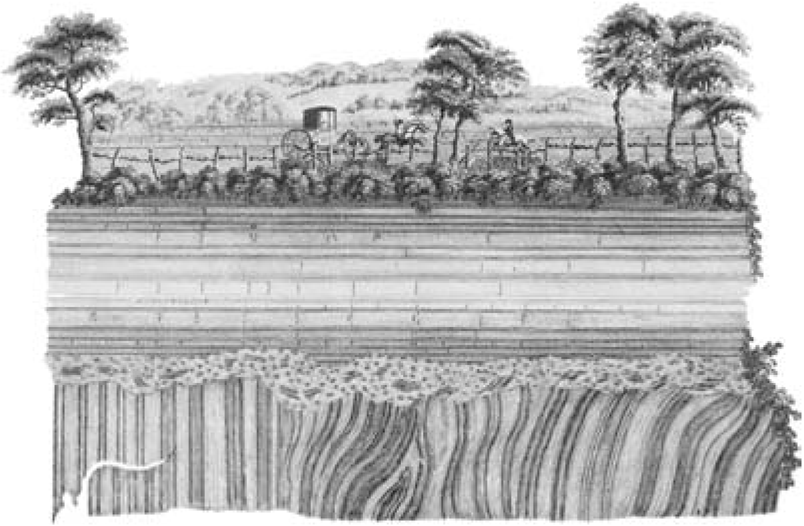

Figure 2. A somewhat idealized sketch of an unconformity observed by Hutton near Jedburgh, Scotland. This sketch, drawn by Hutton's friend John Clerk, appeared in volume 1 of Hutton's *Theory of the Earth, with Proofs and Illustrations,* published in 1795. The sequence of sedimentary layers in this simple 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 disdain 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 late 1890s, 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, beyond 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.

CHAPTER FOUR

Changing Perceptions

In its early years—in the 1950s and 1960s—radiocarbon dating changed people's perceptions of both human and glacial chronology. It didn't actually change the ages of things, of course, but it did change people's understanding of the ages of things, sometimes quite radically. When Libby developed the method, a few other techniques that used radioactivity to probe the chronology of the Earth's past already existed, as will be told later in this book. They, too, were in the early stages of development, and were not yet very sophisticated. But, more important, they were all based on radioactive isotopes with very long half-lives (typically more than a billion years) compared with the 5,730-year half-life of carbon-14. In practical terms, this meant these methods could not access the geologically recent past that became the domain of radiocarbon dating. They simply could not resolve events that had happened during the past 20,000 or 30,000 years. As a result, all the interesting chronology for archaeological and very recent geological events stood on a shaky foundation. Sometimes it involved little more than intuition. Radiocarbon dating quite literally transformed knowledge of this geologically recent swath of time.

Bill Libby's decision to set up an advisory committee to guide his research group in their selection of projects and samples was unusual, but very astute. Unusual because in experimental science, priorities, methods, and sample choices are often jealously guarded from the eyes and ears of potential competitors. Astute because it meant that all the research communities that could benefit from the new method would pay close attention to the results. The committee picked out eleven topics they thought were important and appropriate for radiocarbon dating, and for each they selected a prominent researcher as point man. They circulated details about the research areas and the names of the appointed leaders widely, and anyone who had samples that might contribute valuable age information was urged to contact the committee.

Nine of the research problems they identified were archaeological in nature, and essentially regional in scope, including Peru, the American Southeast, California-Oregon, the Yukon, and Scandinavia, among others. A tenth was geological, involving the timing of advances and retreats of glaciers across Europe, the northern United States, and Canada. The last was "pollen chronology." Pollen grains are produced in vast numbers and spread by the wind, as anyone with a pollen-based allergy knows only too well. But pollen has an upside, too. It is very distinctive—experts can tell what type of plant each pollen grain comes from—and pollen is also remarkably resistant to degradation. In lakes and ponds, pollen grains accumulate along with other sediments (pollen grains accumulate in other places, too, but lakes are especially favorable) and produce a long-term record of the year-to-year regional mix of vegetation. This record in turn is a good indicator of climate, and glacial geologists had been using pollen analysis to track the swings between cold glacial periods and warmer intervals, and to determine whether these changes were local or regional. The problem, however, was to decipher the timing. Radiocarbon dating held out the possibility that accurate ages could finally be deduced for the pollen records, which, until then, had only been useful for determining the relative sequence of events.

The radiocarbon dates produced over the first several years of operation of Libby's University of Chicago laboratory answered many of the questions posed by the advisory committee, and it is not an exaggeration to say that they completely revolutionized the study of both archaeology and glacial geology. Age determination had always been central in these fields, but beyond the time frame of recorded history, many dates were based on informed guesses or, at best, questionable assumptions. In contrast, radiocarbon dates were solidly founded in physics via the law of radioactive decay, and they also could be tested for consistency by multiple analyses of the same sample, or by cross-checking with results obtained by different laboratories. Researchers for whom chronology was crucial became a bit more circumspect in their pronouncements. They realized that both conventional wisdom and off-the-cuff hunches about time scales could now be confirmed by the new dating method—and could also be proved wrong.

One indication of just how powerfully radiocarbon dating affected archaeology came at an international conference in 1990, some forty years after Libby's development of the method. Fred Wendorf, an archaeologist from Southern Methodist University in Texas and a specialist in North Africa, presented a paper in which he said, in part, that "[radiocarbon dating] produced a true revolution in our ideas about the origin and development of almost every known cultural complex [and] profoundly changed our concept of cultural relationships within North Africa, and between North Africa and other areas." He went on to say that radiocarbon dating had rendered obsolete nearly all the chronological relationships *that had been so confidently espoused by the experts* before about 1960 (italics mine). His comments emphasize the importance of reliable and verifiable dates based on radioactivity, as opposed to those obtained in less quantitative ways. His remarks dealt explicitly with archaeology in North Africa, but they are equally valid for other parts of the world.

Carbon-14 dating is now so widespread that there is an entire scientific journal, published three times each year, dedicated exclusively to the results of radiocarbon research. It is called simply *Radiocarbon,* and a typical issue may contain articles about applications in areas as diverse as archaeology, geology, oceanography, and climate change. And that is only the tip of the iceberg. Scientific papers discussing radiocarbon dating appear in many other scholarly journals as well. In the 1950s, however, there was no journal devoted to radiocarbon research. All results from the first few years of work in Libby's laboratory were published in *Science,* the weekly publication of the American Association for the Advancement of Science. *Science* is a prestigious journal with a broad, worldwide readership. Today, researchers vie to have their most important work published there, but the competition is stiff. Many very good papers are rejected, ending up published in other journals that are perceived to have a less exalted status. From that perspective, it is interesting to look again at the early publications by the Chicago laboratory, because today—in spite of their obvious importance—they might not make it into print in *Science.*

The reason is not difficult to grasp. In rapid succession, Libby submitted five separate papers to the journal; they were published between February 1951 and November 1954. The first was coauthored by Jim Arnold and Libby and titled simply "Radiocarbon Dates"; this is the paper described in chapter 3 as reporting ages for about 150 samples. The next four, all with Libby as the sole author, were essentially yearly updates: "Radiocarbon Dates II" through "Radiocarbon Dates V." Each of these papers is little more than a list of dates, together with a detailed description of the samples analyzed. This format was to some extent dictated by the fact that most of the samples had been chosen by the advisory committee, and neither Libby nor his colleagues in Chicago had the expertise to provide interpretations of their results. That would require input from a wide range of specialists. More than 350 different age determinations were dealt with in this way, for samples from geographically far-flung localities. "Just a data dump," today's peer reviewers might say. "No hypotheses to test, no analysis of the significance of the results. This paper should be published in a specialist journal, not in *Science.*"

To be fair, the scientific endeavor has changed drastically since Libby's day. Among other things, there were far fewer options then for publishing data such as the carbon-14 results. And the papers reported results from a new method of potential interest to a broad audience, whom Libby wanted to reach. There is no question that he succeeded in this goal. The published dates were discussed and interpreted widely, both by the specialists who had submitted the samples in the first place and by others in their fields.

The range of materials analyzed for the five papers in *Science* is astonishing. Most common, as you might imagine, are things like charcoal and wood, but also listed are dates for everything from corncobs to human hair, deer antlers, beeswax, and giant sloth dung. Anything that contained carbon and was once alive was fair game. In the second of the series of papers in *Science*—this was after Jim Arnold had left the project—Libby reported a date for the Dead Sea Scrolls. Arnold, as you may recall, had not wanted to work on samples with specific religious significance. The sample Libby analyzed was actually a piece of the linen wrapping of the scrolls, and his result confirmed that the material dated from 2,000 years ago. Another of the papers reports a date for frozen grasshoppers. It's clear that Libby was having fun, enjoying the fruits of having developed a new dating method. The grasshoppers were from a glacier in Yellowstone National Park, and their radiocarbon content was only slightly lower than the contemporary value. Libby calculated their age as 45 years, but, within the fairly large margin of uncertainty in the measurement, they could be anywhere from zero to about 200 years old. Most probably, they were frozen into the glacier during the 1870s or 1880s, when hordes of grasshoppers plagued the western United States.

Some of the dates in the *Science* papers provided only minimum ages, the results given in terms such as "older than 17,000 years" or "older than 25,000 years." In these cases, the counting rates were barely distinguishable from the background rate observed with no sample in the counter, indicating that nearly all the carbon-14 initially present in the sample had decayed. To an outsider, such results might seem of little value. But to anyone seeking to establish an absolute chronology for an archaeological site or a glacial deposit, even a minimum age is a valuable piece of information.

A word about "errors" and "uncertainties" may be useful here. This is a somewhat technical topic, but an important one to understand. Dates reported in the scientific literature are typically given in the form "5,000 years, plus or minus 300 years." This simply means that, to a high degree of probability (which is usually specified precisely when a date is reported), the true age of the sample lies between 4,700 and 5,300 years. It is as likely to be 4,795 years, or 5,123 years, or anything else in that range, as to be exactly 5,000 years. But it is much less likely to fall outside the range. And an age farther away from that range is even less likely than one close to it. The "plus or minus" part takes into account the uncertainty in the data used to calculate the age—for example, uncertainty in the measured count rate in a carbon-14 dating experiment. The usual analogy is coin tossing. We all know that, if you have the patience to toss a coin a million times, the split between heads and tails will be very close to fifty-fifty. The uncertainty of the result in that experiment is small because you have carried out a large number of trials. But, if you toss the coin only three or four times, you might get all heads, or all tails, or some other lopsided result. In this case, the result has a large uncertainty, because the next time you perform the same experiment of three or four tosses, you will be likely to get quite a different result. The more times you perform this experiment, the closer the combined result will be to the correct fifty-fifty split. So, too, with counting radioactive decays from carbon-14 (or any other radioactive isotope). The smaller the number of counts (e.g., for old samples containing little radiocarbon), the higher the uncertainty in the result. Uncertainties, however, are not just related to a sample's age; they depend on many other factors as well, including sample size and type, and details of the measurement technique. They are inherent in all the dating methods discussed in this book. But they can be quantified by well-known statistical techniques, and they are always reported along with the dates, providing a good sense of how reliable a particular age determination really is. Sometimes they are referred to as "errors," but that term implies a mistake or problem, and I prefer (and will use throughout the book) the term *uncertainty* because that is really what they are.

Libby was awarded the 1960 Nobel Prize in Chemistry in recognition of his development of radiocarbon dating. The citation from one of those who nominated him read: "Seldom has a single discovery in chemistry had such an impact on the thinking of so many fields of human endeavor. Seldom has a single discovery generated such wide public interest." That research in nuclear chemistry involving a rare radioactive isotope should generate any public interest at all might at first seem remarkable. But, as we have seen, radiocarbon dating is especially useful for dating events in human history, and Libby's work struck a chord with the public. Who would not be intrigued by the discovery of a way to measure the age of Egyptian kings, or to date man's first foray into North America?

The agreement between the early radiocarbon ages and those determined from historical or other reliable evidence—especially for those first few samples included in the "curve of knowns" (see figure 7 on page 66)—seemed almost too good to be true. But, as more samples were analyzed during the 1950s, and as the measurement uncertainties decreased because of improved experimental methods, some disturbing trends showed up. Occasional "fliers"—dates that seemed to be completely wrong—were not the problem; these could usually be explained by human error such as sample mislabeling, or perhaps by contamination of the sample with material of a different age (I will come back to the problem of contamination later in this chapter). What was troubling, however, was that there seemed to be a consistent trend of samples being "too young" by up to several hundred years. This discrepancy could only be discerned in cases where there was firm archaeological evidence for the true age, but there were enough of those to cause concern. Was there a simple explanation, or was radiocarbon dating turning out to be unreliable?

The standard reaction among those who debunk dating based on radioactivity is to seize on such apparent discrepancies and declare that *all* ages measured using these techniques are nothing but fabrications. The more rational response, however, is to ask where the problem might lie. And the first step in doing that is to look at the assumptions that underlie the dating method.

In the case of radiocarbon dating, determining the age of a sample is, in principle, quite straightforward. The first step is to measure its carbon-14 content accurately, and the second is to plug this measured value into the radioactive decay equation and calculate the age. The equation is the same one that Ernest Rutherford formulated from his observations of the systematic decay of the radioactive gas radon. Although I have avoided using equations in this book, the general decay equation (see appendix C), adapted for carbon-14, is reproduced below because it is so important. The radioactive decay equation is actually not difficult to understand, and, if you make the effort, it should help to clarify the nature of radioactive decay and its application to dating. Figures 5 and 7 on pages 56 and 66 both show the equation in graphical form (as solid curved lines). It is written as.

$$^{14}\mathrm{C} = (^{14}\mathrm{C})_0 e^{-\lambda t}$$

What the equation says is that the amount of carbon-14 in a sample (this is the measured value, represented by the term on the left-hand side) is equal to the amount of the isotope present at time zero, $(^{14}\mathrm{C})_0$, times the expression $e^{-\lambda t}$. The symbol *e* is the standard representation for a mathematical constant (the number 2.71828 . . . , which is used as the base for natural logarithms), and λ is another constant that characterizes the rate at which carbon-14 decays (it is directly related to the half-life). The age to be calculated is represented by the symbol *t* for time.

The two major assumptions in radiocarbon dating involve the two terms $(^{14}\mathrm{C})_0$ and λ on the right-hand side of the equation. If those two parameters are known accurately, then the only quantity in the equation that *isn't* known is *t,* the age of the sample, which can then be calculated quite easily. So the question has to be asked, Do we know those two parameters accurately enough for the method to work properly?

When Libby embarked on his development of radiocarbon dating, the half-life of carbon-14 (and therefore the constant λ) was not well known. Values ranging from 5,000 years to over 25,000 years had been reported, and several of these estimates had large uncertainties. Libby and several of his colleagues decided to make their own measurement for use in the dating work, and they averaged the result they got with what they considered to be the most accurate of the previous determinations. In this way they came up with a half-life of 5,568 years, with an uncertainty of just plus or minus 30 years.

But, as it turned out later, this result—which became known as the "Libby half-life"—was slightly off. More recent determinations place the half-life of carbon-14 at 5,730 years; this is the accepted value today. The difference is small, just under 3 percent. For the most part, it had no effect on Libby's work because the measurement uncertainties were at least this large for most of the early radiocarbon dates. On the other hand, it did mean that all ages calculated using the Libby half-life were, in a statistical sense, systematically on the low side of their true ages. As more and more data accumulated, this discrepancy became obvious, but it was also easy to correct later on, simply by recalculating the dates using the newer, more accurate half-life value.

The parameter $(^{14}C)_0$ in the decay equation, however, is more problematic. It represents the carbon-14 content of the sample material at the time the plant or animal died, and it obviously can't be measured directly. Ernie Anderson's measurement of the "contemporary assay" showed that the radiocarbon content of living things is the same everywhere on Earth today, and it seemed reasonable to assume, at least as a first approximation, that this value also characterized organic carbon in the past. The agreement illustrated in Arnold and Libby's "curve of knowns" reinforced this conclusion, and suggested that it was valid at least over the past few thousand years. But beyond the reach of the historical record, there seemed to be no obvious way to test this assumption. Or was there?

One of the scientists whom Jim Arnold instructed in his minicourses on radiocarbon dating was a brilliant Austrian chemist named Hans Suess, who had been invited to visit the University of Chicago in 1949. Suess had heard about Libby's carbon-14 work and was interested in its potential as a dating tool. While he was in Chicago, he took every opportunity to learn as much as he could about the new technique.

Suess never did return permanently to Austria. He ended up staying in the United States, and went on to an illustrious research and academic career. Some years after leaving Chicago, he became a professor of chemistry at the University of California at San Diego, where he had the reputation of being the quintessential absent-minded professor. That trait was apparently evident quite early on, because Arnold says that while most of the "students" who visited Libby's lab to learn about radiocarbon dating took copious notes and were extremely attentive, Suess just wandered in, listened for a while, and went away again. But this casual approach, like his veneer of absent-mindedness, disguised a sharply perceptive mind. Suess had quickly assimilated the basics. He didn't need to take notes about Arnold's procedures because he already had his own ideas about how to improve the method. Suess soon left Chicago for Washington, D.C., where the U.S. Geological Survey (USGS) had asked him to set up a radiocarbon dating laboratory. Over the next few years, he and his colleagues carried out a large number of key carbon-14 analyses, concentrating especially on the chronology of ice age glaciation in North America.

Suess's most important contribution to the rapidly developing field, however, came after he left the Geological Survey and moved to San Diego. There he began collaborating with researchers at the Laboratory of Tree-Ring Research, part of the University of Arizona in Tucson. Dendrochronology—the science of tree-ring counting—was already a valuable tool in archaeology. With care, by counting back from the present, each annual growth ring can be assigned to an exact calendar year. In their "curve of knowns," Arnold and Libby had included dates from the inner portions of two ancient trees, illustrating that the radiocarbon and tree-ring dates agreed (see figure 7 on page 66). That result demonstrated that wood in a growing tree ceases to exchange carbon-14 with the environment once it is formed (otherwise the dates would not have agreed). Each growth band captures the carbon-14 signature of the atmosphere during the year it grows, and then becomes a kind of sealed time capsule.

Researchers at the Tree-Ring Laboratory had been able to push dendrochronology back far beyond the time span of living trees by patching together overlapping growth-band sequences. Because of year-to-year changes in temperature and precipitation, the appearance of tree rings varies, especially their thickness. Two or three years of drought produce two or three years of thin rings; a wet year produces a spurt of growth and a thick tree ring. Over time, a unique pattern comes to characterize all the trees in a region. By painstakingly matching up overlapping patterns between living and dead trees, and then between increasingly older dead trees, researchers had been able to put together a continuous record that could be traced back several thousand years. Wood from an archaeological site could often be dated simply by comparing its tree-ring pattern with this master record.

Suess understood the potential of "calibrating" radiocarbon ages by using tree rings. Because each ring records the carbon-14 content of atmospheric CO_2 in the year it grows, he could test Libby's assumption that the carbon-14 content of living matter—the parameter $(^{14}C)_0$ in the decay equation—had not changed over time by measuring radiocarbon in rings of accurately known ages. Some of the wood investigated at the Tree-Ring Laboratory—notably from no-longer-living bristlecone pines (see figure 8) that grow at high elevations in the mountains of California—was as much as 7,000 years old. If Suess could measure the "radiocarbon age" of such samples at closely spaced intervals from the present back to 7,000 years, he would have a much more detailed curve of knowns than the one Arnold and Libby had published. If the tree-ring and radiocarbon results agreed, fine; if there were discrepancies, it

Figure 8. A dead bristlecone pine, named the "Colossal Ghost" by its photographer, Leonard Miller. Not only do these trees have very long lives, but, in the arid climate where they grow, their wood resists decay long after death. Scientists can compile a long, continuous tree-ring record by matching ring patterns. Photograph copyright Leonard Miller.

would imply that $(^{14}C)_0$ had varied—and also, the data could be used to adjust and correct dates measured for unknown samples.

Actually, when Suess began his work on tree rings, he was aware that there might be differences between his radiocarbon dates and those obtained by counting rings, because Hessel de Vries, a Dutch scientist, had already completed similar work on wood from European trees. His results, published in 1958 and 1959, showed that there indeed were significant discrepancies, and, importantly, that the offsets were not constant (as would occur if they were due only to an incorrect half-life). De Vries attributed this finding to natural variations in the amount of carbon-14 in the Earth's atmosphere in the past. The discrepancies were immediately dubbed the "de Vries effect."

However, de Vries died tragically in 1959 at a young age, while Suess continued working on radiocarbon dating of tree rings. In 1961, he published data that ranged back to approximately 3,000 years, and, later, in 1969, he extended the range to 7,000 years. Today, he is the scientist most closely associated with the early calibration data. By measuring closely spaced samples through 7,000 years of history, he was able to identify and analyze both short- and long-term trends in the data.

Suess's results, like those of de Vries, showed that the offset between radiocarbon and tree-ring dates changes in systematic ways. There are gradual, long-term (thousands of years) variations, but also an abundance of shorter-term (hundreds of years) wiggles superimposed on those longer variations (see figure 9). De Vries had been right. The only explanation for these patterns was that the amount of carbon-14 in the ancient atmosphere must have varied with time. In retrospect, it is easy to say: Of course! Why would anyone expect the radiocarbon content of the atmosphere to remain constant over thousands of years? Libby himself probably recognized that his assumption would only be true to a first approximation. The work of de Vries and Suess recalls an aphorism attributed to Enrico Fermi, the Italian physicist who was instrumental in building the world's first nuclear reactor at the University of Chicago: "If you make a measurement and get what you expect, you have made a measurement. It you don't get what you expect, you've made a discovery."

The wiggles in atmospheric carbon-14 discovered from the tree-ring data were definitely an important discovery, and, as we will see later in this chapter, they have implications that extend beyond radiocarbon dating. But their immediate significance was their demonstration that one of the fundamental assumptions of the method was not really valid. All was not lost, however, because the same data that revealed the discrepancies could be used to correct them. By 1969, Suess's "calibration curve" was already quite detailed, and more tree-ring samples were being analyzed every day. With good coverage for a particular age range—like that in figure 9—the true age of a sample could be determined directly from the calibration curve. It's easy to see that, for intervals over which the curve rises smoothly and rapidly, such as between about 3,320 and 3,420 years (calendar age),

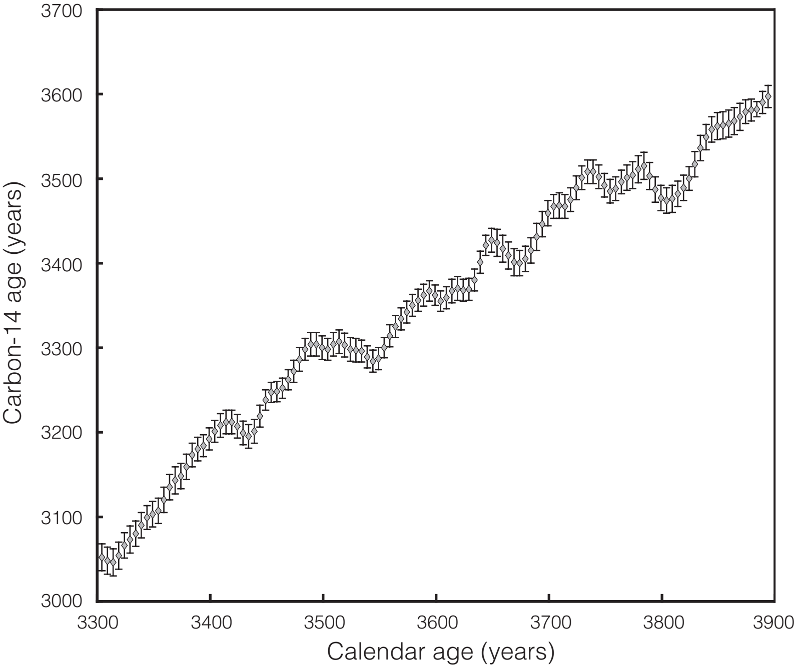

Figure 9. Part of the radiocarbon calibration curve, in which calendar (actual) ages, based on tree-ring counts, are plotted against ages calculated from carbon-14 measurements. Because carbon-14 in the atmosphere has varied in the past, the two do not agree precisely. Uncertainties in the carbon-14 data are shown by the vertical bars at each data point; the consistency of the measurements is remarkable, allowing even small variations in past atmospheric carbon-14 to be identified. The short-term "Suess wiggles" are very evident in this example, but the gradual, longer-term variations are not, because of the short time period shown. Data for this graph are from the most recent radiocarbon calibration, by Paula J. Reimer et al., *Radiocarbon* 46 (2004): 1029–58.

this approach is quite sensitive. For other regions of the chart, such as that between 3,750 and 3,850 years, ambiguities arise. In fact, several "correct" ages may be permissible because of the wiggles.

All this manipulation can seem pretty confusing if you are encountering the details of radiocarbon dating for the first time. In a vague way, it seems to the uninitiated that radiocarbon daters are somehow fudging their results. But, in reality, the procedure is a straightforward result of experimentation and observation. The carbon-14 data for tree rings from the western United States show exactly the same wiggles and variations at exactly the same times as those from Europe. The agreement is impressive—not only do the data come from laboratories using different measurement techniques, but also the annual growth-ring patterns in the trees reflect local climatic variations, and are therefore different from region to region. In spite of these variations, however, there is worldwide consistency in the calibration data, indicating that the tree-ring ages are accurate and that the radiocarbon measurements closely track global variations in the amount of carbon-14 in the ancient atmosphere, even when they were quite small. (A very small offset occurs between the Northern and Southern Hemispheres because of the details of carbon-14 production and mixing in the atmosphere, but this phenomenon is well understood and does not affect the overall conclusion.) In effect, the calibration curve provides a value for the term $(^{14}C)_0$ in the decay equation. This value is not constant, as was initially assumed, but as long as its variability through time is known, it can be taken into account and will not affect the accuracy of the dates. To prevent confusion, in the scientific literature, the results of carbon-14 analyses are reported, by convention, as uncorrected "radiocarbon ages" (the vertical axis in figure 9). These are calculated from the laboratory measurements using agreed-upon values both for the half-life and for the present-day carbon-14 content, $(^{14}C)_0$. The true age of the sample can then be read from the appropriate portion of the calibration curve. And, again to avoid confusion, the calendar (true) ages are always referred to 1950. Thus, a sample dated as 3,000 years old from the calibration curve was 3,000 years old in 1950; in 2000, it was 3,050 years old, and so on.

Quite aside from the implications of the calibration curve for dating, it is also a window through which to examine other phenomena that have affected the Earth in the past. When Suess showed his data to

Libby and pointed out that there seemed to be some regularity to the wiggles, Libby reportedly said, "If this is true, then the radiocarbon values should be a most interesting geophysical parameter." That has certainly turned out to be the case. As de Vries first suspected, the wiggles—and also the longer-term variations—are caused by past changes in the carbon-14 content of the atmosphere. But, in a sense, that is only a symptom. The question is, What caused these variations?

As is true for many natural phenomena, the pattern of changes revealed in the calibration curve does not have a single cause; instead, it is the result of several different processes. One of these has to do with the way carbon cycles through the various "reservoirs" in which it resides on Earth, such as the atmosphere, the oceans, and living organic matter. But more important is the strength of the cosmic ray bombardment that produces carbon-14 in the first place. To a large extent, both the wiggles and the longer-term variations are a kind of fossil record of this interaction—the greater the intensity of cosmic ray bombardment, the more carbon-14 is produced, and vice versa.

Only a small fraction of the cosmic rays traveling through space toward our planet actually make it to the atmosphere, because the Earth's magnetic field acts as a shield, deflecting most of the particles away. And the magnetic field is constantly changing; direct measurements show, for example, that its strength has decreased by about 10 percent since the eighteenth century, and much greater changes have occurred over longer time scales. When the field increases, fewer cosmic ray particles can penetrate through; when it decreases, more make it to the atmosphere. Such changes therefore affect the production of carbon-14, and most researchers believe magnetic field changes are behind the long-term variations evident in the calibration curve. These variations, however, are too gradual to explain the short-term wiggles. The consensus is that these are related to changes in the sun's activity.

It might seem strange that the sun can affect carbon-14 production in the Earth's atmosphere. But the sun produces its own magnetic field, which extends out into space far beyond the Earth. When the sun is active, this field strengthens, and fewer cosmic ray particles make it to the Earth's atmosphere, leading to lower carbon-14 production. This has been verified in an ingenious way. Times of high solar activity are marked by an increase in visible sunspots, and vice versa. Because sunspots have intrigued observers for millennia, there is an almost continuous record of their occurrences since at least 2,000 years ago, when Chinese scholars began recording them. To the extent that this record can be compared with the radiocarbon calibration curve, the two agree: times in the past when numerous sunspots were noted correspond to lower carbon-14. The active sun generated a stronger magnetic field, more effectively shielding the Earth from cosmic rays. And there is another possible correlation as well. Because variations in the sun's activity affect the amount of solar energy reaching the Earth, they can affect climate. Thus the radiocarbon calibration curve may also harbor information about past climate change.

Hans Suess was well aware that his data extending back to 7,000 years held important clues to past interactions between cosmic rays and the Earth's atmosphere. He put a lot of effort into trying to understand the significance of the small-scale variations in the curve, and they soon became known as "Suess wiggles." But he was bemused by the reaction of many of his fellow scientists. He wrote later that it was of great interest to him to "[understand] the psychological causes that led the great majority of investigators to deny, for many years, the existence of regular deviations of the carbon-14 values, the so-called 'wiggles,' from a smooth line." He was not the first to be perplexed by the tendency of some researchers to resist new ideas, even in the face of compelling experimental evidence. Even scientists, he thought, prefer straight lines and regularity to the messy pattern of wiggles his data revealed.

I hope it's clear from the last few pages that most of the radiocarbon dates that appeared to be "wrong" based on archaeological evidence—especially in the early days of the technique—were not wrong at all. The measurements were accurate, and the age calculations appropriate. What made them appear "wrong" is, first, that, because of past variations in its production rate in the atmosphere, the amount of carbon-14 in living matter has not always been the same as it is today, and, second, that Libby's initial half-life determination was slightly in error. The calibration curve, which has now been extended back tens of thousands of years, even beyond the time scale accessible through tree-ring studies, takes care of those effects. With accurate knowledge of carbon-14's half-life, and of carbon-14 variations in the past, radiocarbon measurements give a true measure of a sample's age.

Keeping in mind that the calibration curve is continually being improved, as are the instruments for making carbon-14 measurements, let's take a look at how early successes quickly put radiocarbon dating on the map in two important research areas: glacial geology, and the entry of humans into the Americas. Although more recent work has sharpened the details, the research by Libby and his colleagues, and by a few other early practitioners of radiocarbon dating, laid out a remarkably accurate framework on which all subsequent investigations have been based.

During the first half of the twentieth century, glacial geology was an especially popular and well-studied aspect of the earth sciences in North America and Europe. The reason is not difficult to understand. Throughout the northern United States and most of Canada, and in Scandinavia, Great Britain, and the northern fringes of Europe, the surface landscape has been heavily influenced by the great glaciers of the ice age. Signs of their presence are everywhere if you know where to look. You don't even have to go out into the countryside—even in Central Park, in the heart of Manhattan, you can see the surface polish and scratches left on rocky outcrops by the sandpaper-like action of flowing, grit-filled glaciers. In other places, huge boulders, carried by the ice and left stranded when it melted, sit in farmers' fields, too heavy to move. Mounds of rocky rubble scraped up by glaciers and dumped along their borders have created gently undulating topography in the same regions. The fertile fields of the American Midwest were developed on the finest grains of that rubble, winnowed and transported by the wind. As the glaciers melted back, lakes developed in low-lying areas along their margins, depositing layer upon layer of characteristic glacial sediments. All these features were mapped out in great detail by geologists, beginning in the nineteenth century. By using the cardinal rule of stratigraphy, that young material always covers or cuts through older material, geologists were able to work out the relative chronology for some of the events of the ice age. But they had to rely on crude estimates of how fast natural processes occurred—how long it took soil to develop on glacial rubble, for example, or how fast ice flowed or melted back—as a guide to the actual time scales. And, because the glacial deposits are not always continuous, it was difficult to correlate from one region to another even over reasonably short distances, and virtually impossible to determine whether deposits in Europe and North America had been laid down at the same time. This made it hard to know whether the glacial deposits reflected global or simply regional changes in climate, and also to work out the causes of the glaciation. But nearly all estimates of the timing of glacial activity put at least some of it in the geologically recent past, thousands or tens of thousands of years ago. Thus glacial geology was a field ripe for radiocarbon dating.

Richard Foster Flint, the lone geologist on Libby's advisory committee, was the most prominent glacial geologist of his day, a professor at Yale and an eloquent speaker. Much of his research involved mapping and interpreting glacial deposits—he virtually single-handedly put together the first glacial map of Connecticut. Flint was acutely aware of the importance of accurate chronology for this work, and to him radiocarbon dating seemed to be a godsend. He could easily have kept the Libby laboratory busy full-time with samples related to the ice age. However, archaeologists were also clamoring for dates, and, in the first list of radiocarbon ages in *Science* in 1951, the majority of results reported by Arnold and Libby were archaeological. Nevertheless, a few of the samples had been chosen for their glaciological significance, most on Flint's recommendation. They included peat and mud rich in organic material from several sites in Europe, and also a number of samples from North America. Most important was a group of samples from a location known as the Two Creeks Forest Bed.

Two Creeks has acquired worldwide fame among radiocarbon chronologists. The site lies in Wisconsin, along the western shore of Lake Michigan, and long before radiocarbon dating became a reality it had provided a fascinating and almost unparalleled snapshot of ice age processes in action. By the end of the nineteenth century, geologists had established that during the most recent ice age there had been, at a minimum, four major advances and retreats of glaciers across northern North America. The last of these they named the "Wisconsin" glaciation because some of its most striking effects are seen in that state. (To preserve and highlight this legacy, in 1971 the National Park Service and various local organizations established the Ice Age National Scientific Reserve of Wisconsin, which includes a one-thousand-mile-long Ice Age National Scenic Trail that wends its way across the state, passing through and over the glacially sculpted landscape.) The glacial sediments at the Two Creeks locality had been assigned to the Wisconsin glaciation, and geologists had established that they revealed a complex series of events probably representing the very last gasps of the Wisconsin. The most striking feature of this site was the preserved remnants of a forest that had been literally toppled over by the last advance of the great ice sheets. The event was, so to speak, frozen in time. As the ice melted away, a huge lake formed—a precursor of present-day Lake Michigan—and deposited mud and silt over the destroyed forest, sealing it off from further disturbance. It was an ideal target for radiocarbon dating: an age for this site would establish the time of the last significant glacial episode in this part of the country, and possibly North America as a whole.

To give you an inkling of the glacial record preserved in the Two Creeks sediments, figure 10 shows an idealized cross-section through a bluff along the Lake Michigan shoreline in the area. Like the sketch James Hutton's friend made of the rocks in Jedburgh, Scotland (see figure 2 on page 10), this seemingly simple picture provides a wealth of information about past events. First, at the bottom is a layer of loose, rubblelike sediment characteristic of the material that glaciers scoop up and push along, and then leave behind when they melt, commonly referred to as "glacial till" by geologists. Its presence is an unequivocal sign of a period of glaciation. Overlying the till is a layer of much finer material, clay and sand, exhibiting its own layers and evidently deposited in a lake that covered the site after the glaciers receded. Above the lake sediments sits a soil horizon (labeled "forest bed debris" in figure 10), dark and peaty, containing bits of still-obvious pine needles, pinecones, and other organic material. Occasionally there is a broken tree trunk, standing vertically, its roots still anchored in the soil layer. These remnants record a time when the lake receded, vegetation flourished, and trees grew. But again the region was flooded, as revealed by another layer of clay and sand covering the soil and engulfing the tree trunks. On top of that is a further layer of till, signifying another glacial advance. It still contains some of the tree trunks sheared off by the glaciers, nearly all of them lined up in the local direction of ice movement. Still higher up on the bluff is yet another layer of lake sediments, deposited as the glaciers melted, again flooding the land.

Most of us wouldn't give a second thought to a sequence of layers like this exposed on a hillside. But, to a geologist, every layer is brimming with information about the end of the Wisconsin glacial period, which is why the Two Creeks locality is so important. To help elaborate on the story told by the sediments, countless samples have been taken from the various layers and carefully examined for pollen grains, plant remains, and shells. Together they provide a comprehensive picture of the local vegetation and give clues about the climate. Of most interest, as far as radiocarbon research is concerned, are the soil layer and the broken trees that are the remains of a forest flooded by rising lake waters and bulldozed by the advancing glacial ice.

Preservation at the Two Creeks site is so good that an amazingly detailed picture has been constructed of the forest ecosystem. The wood is mostly spruce and hemlock, typical of northern forests today, and some of

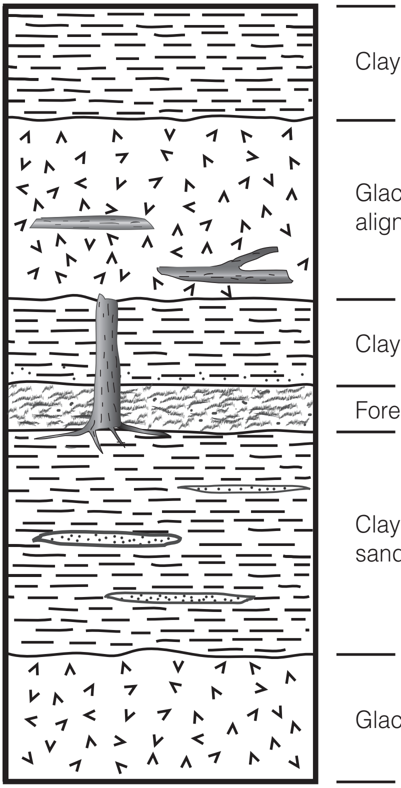

Figure 10. An idealized cross-section of the sedimentary layers at the Two Creeks locality. Beds of glacial till record two glacial episodes, the second of which sheared off parts of trees in a forest that had existed for at least sixty years. Libby's radiocarbon dates on material from the "forest bed" showed that the last glaciation of the area occurred 11,400 years ago. This drawing is based on information in a monograph by C. E. Prouty for the 1960 field excursion of the Michigan Basin Geological Society.

the trunks even retain remnants of bracket fungus, as well as holes from at least two different species of bark beetles. Mosses, plants, and mollusks that lived in the forest have also been identified. Tree-ring counts show that the average age of the trees was about sixty years when the forest was flooded and cut down by the advancing glacier. By selecting a specific block of rings for radiocarbon analysis, it might be possible to date the last surge of Wisconsin glaciation to within a few tens of years.

Prior to carbon-14 dating, geologists had estimated that the ice advance recorded by the sheared-off Two Creeks trees dated to somewhere between 20,000 and 25,000 years ago. It is not surprising, then, that the Arnold and Libby radiocarbon age for wood from the soil layer caused quite a stir: it was only 11,400 years. This was completely unexpected. Until then, no one had imagined that ice had reached so far south in North America so recently.

The Two Creeks result was a turning point in understanding glacial chronology, and for some it ranked as the most important date in the whole of the 1951 Arnold and Libby paper. According to Jim Arnold, Richard Foster Flint accepted the date without great surprise; perhaps he already had an inkling that the much older age conventionally associated with the site was incorrect. For some other researchers, though, it was a controversial result. But, as more ages were measured for glacial deposits, and as several new laboratories began churning out radiocarbon dates, it became clear that the Two Creeks age was not an anomaly. The height of the Wisconsin glaciation, the time of maximum ice, had indeed occurred at around 20,000 years ago, when glaciers reached far south of the Great Lakes, covering much of present-day Illinois, Indiana, and Ohio. Sometime after this, they began to melt back, but it was a slow process. Not until nearly 10,000 years ago did they begin their rapid and irrevocable retreat in the face of a warming climate. In between, especially along the margins of the ice sheet in the northern United States, there were local advances and retreats in response to small changes in climate conditions. During cold periods, lobes of ice would reach down valleys like the fingers of a hand, only to draw back again when temperatures rose. The Two Creeks age dated the very last of these episodes.

Since Arnold and Libby's work, the geography of ice margins and the advances and retreats of localized ice lobes have been meticulously documented using evidence similar to that found at Two Creeks. Most of the important localities have been radiocarbon dated, providing a detailed chronology of ice movement. The ages have been crucial for correlating events at widely separated locations, and they have shown that most swings in climate, even quite small ones, were simultaneous both in Europe and North America.

Given its importance, the Two Creeks Forest Bed itself has been redated by other laboratories. With the benefit of the calibration curve, which had not even been thought of when Arnold and Libby published their first dates, the later analyses gave a slightly older age. The difference, however, was only a few hundred years, and it did not change the conclusion that retreat of the Wisconsin ice sheet occurred much more recently than had once been thought.

Libby and his group had to rely on Richard Foster Flint and other geologists to advise them about important samples for glacial chronology, but they did have a connection with archaeology, however tenuous, through Jim Arnold's knowledge of Egyptian history. Partly for that reason, many of the early archaeological samples that they dated came from Egypt. Libby also asked Arnold to be a liaison between the laboratory and archaeologists, and sent him to a number of archaeological conferences. Arnold took this responsibility seriously. In addition to attending meetings, in the summer of 1949—after working flat out for months in the laboratory—he took his "vacation" by going to an archaeological field camp.

The camp was at a permanent Field Museum site in western New Mexico, and it provided Arnold valuable insight into the intricacies of archaeological sampling. It also introduced him to New World archaeology. Libby himself had an abiding interest in using radiocarbon dating to work out the timing of human migration into the Americas, and because several members of the advisory committee, including the chairman, Fred Johnson, were also deeply involved in New World archaeology, it was natural that this soon became a focus of dating activity in the Chicago laboratory. It was a focus that paid off handsomely, because the data Libby and his colleagues collected during their first few

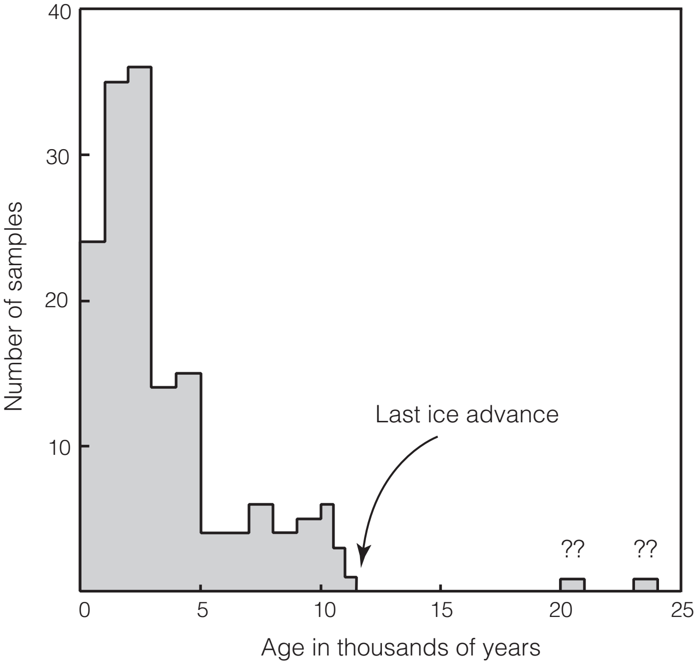

Figure 11. For his 1960 Nobel lecture, Libby plotted a bar graph like this one of all existing radiocarbon dates for North American archaeological sites. He emphasized the link between the end of the Pleistocene Ice Age and the spread of early people by showing the time of the last ice advance as determined from his date for the Two Creeks site (11,400 years).

years of work provided the initial chronological framework for American archaeology.

By the time of his Nobel Prize lecture in 1960, Libby was able to present a striking bar graph that included all radiocarbon dates then available for North American archaeological sites (see figure 11). An important feature of the graph is the very abrupt cutoff in ages near 11,000 years ago; only two sites gave older dates, and both were thought to be questionable, possibly because of contamination. (Although I have said little about contamination, it is a serious issue for radiocarbon dating. For old samples that contain very little carbon-14, addition of even a small amount of “modern” carbon can be disastrous. Incorporation of just a few minute root hairs from living plants that penetrate into charcoal at an archaeological site, for example, or fungus growing on a museum sample, will make the measured age much too young. “Dead” carbon from fossil fuel–based products such as paraffin or oil can result in an age that is far too old. Many apparently aberrant radiocarbon dates, especially in the early days before the severity of the problem was realized, were the result of just such contamination.)

Recall that the Two Creeks glacial deposit, dated by Arnold and Libby at 11,400 years, was thought to record the last significant advance of ice on the North American continent before the glaciers melted away entirely. To Libby and many others, the absence of archaeological sites older than this was no coincidence. Extensive peopling of North America, they concluded, followed the retreat of the great continental-scale ice sheets of the Pleistocene Ice Age. Libby marked the Two Creeks age on his bar graph to emphasize this conclusion.

Even today, countless analyses later and almost half a century after Libby first showed this graph, it is still the case that most radiocarbon dates for humans in the Americas are less than 11,400 years, although there are significant exceptions. There is also still a vigorous debate about the extent to which glaciers of the Pleistocene Ice Age aided or hindered migration from Asia into and across the Americas. But at the beginning of the radiocarbon work, the picture was not nearly so clear. One of Libby’s first attempts to analyze an ancient North American site using radiocarbon—a site that he thought would date to the earliest habitation of the New World—produced an age that was much younger than the time of the glaciers. It was a locality characterized by artifacts linking it to what archaeologists refer to as the Folsom culture.

Folsom is a small town in northeastern New Mexico. In 1926–27, arrowhead-like stone points were found there, mixed together with bones from a now-extinct type of bison, a discovery that caused great excitement because it placed humans in New Mexico during the last glacial period, when bison were abundant. Beyond that general observation, however, there was no way to date the site. Eventually, additional "Folsom" sites were discovered in other regions, all characterized by the same distinctive stone points. A few of these were in places that could be correlated with specific glacial deposits, which, through a fairly tenuous line of reasoning, were thought to be between 10,000 and 25,000 years old. Most workers favored the older end of the range.

Arnold and Libby included a charcoal sample linked to the Folsom culture in their first published list of radiocarbon dates. The result was a surprise: 4,283 ± 250 years. This was clearly much younger than any of the earlier estimates suggested, and, if the date held up, it would mean that what appeared to be one of the oldest Native American cultures was actually quite recent. Although they were confident about their analysis procedures, Libby and Arnold were suspicious of the result and wondered if the sample had been contaminated with young carbon, or if there was some other difficulty they were unaware of. In the end it turned out to be a classic case of improper sampling, and an example of the importance of careful field documentation. When the charcoal was collected in 1933 (it had been stored away from then until the analysis), it appeared to be lying within a soil layer that contained both animal bones and the distinctive Folsom stone points. But the unexpectedly young age prompted reexamination of the site, and it was discovered that the charcoal came from a channel that cut into and through older layers. Although it appeared to be at the same level as the bones and stone points, it was actually much younger. Once this problem was recognized and new samples from this and other sites were analyzed, it became clear that the most reliable Folsom ages fell in the range of 10,000 to 11,000 B.P. (before the present).

However, it was also discovered that Folsom sites are not the oldest evidence for humans in North America. At some localities, slightly different varieties of stone hunting points occur; initially it was thought that these were simply regional variations, or perhaps weapons used for hunting different types of game. But, in some places—notably at Clovis, New Mexico—they appear in layers that lie *beneath* the typical Folsom points.

This indicated that they were older, and soon archaeologists began to distinguish between Clovis and Folsom cultures. Obviously, Clovis sites became another target for radiocarbon dating, and the results confirmed their antiquity. Clovis sites consistently gave dates that were a few hundred years older than those characterized by the Folsom artifacts, and there seemed to be little or no overlap between the two cultures.

With these results, the radiocarbon dates of both glacial deposits and archaeological sites in North America seemed to be painting a consistent picture. As the last severe glaciation of the Pleistocene Ice Age waned, early people spread into the United States. Clovis people were the first widespread hunters, making distinctive stone points for their weapons and hunting large game such as mammoths. Within a few hundred years, however, a new culture appeared, making smaller and finer stone points and apparently taking over from its Clovis predecessors as the dominant hunters in North America.

The notion that the Clovis people were the first important culture to populate the Americas has been prevalent from the time of the early radiocarbon analyses until quite recently, and the few ages that seemed to indicate there were even older inhabitants, before that key date of about 11,400 years ago, were viewed with suspicion. But it is now evident that some sites really are much older. One is Monte Verde in southern Chile, where repeated and carefully scrutinized radiocarbon results provide strong evidence for human occupation at approximately 12,500 years B.P. Monte Verde is almost as far south as one can go in the Americas, and, if humans migrated into North America from Siberia and spread southward, as seems to be the case, it is obvious that at least some people crossed over long before 12,500 years ago. That, however, is something of a puzzle, because within the United States and Canada almost all ages are much younger. Some archaeologists think that the earliest migrants could have taken coastal routes, avoiding the extensive inland glaciers that then existed and making their way south to ice-free coastal Oregon and California before spreading inland or farther south. Firm evidence for such migrations is lacking, but it has been argued that because sea level was much lower at the time, any sites in low-lying coastal regions have since been submerged under rising seas.

Radiocarbon dating, then, brought the earlier fuzzy chronology of North American prehistory into sharp focus. By providing accurate ages for the deposits of the last great ice sheets and the campfires of paleoindians, it enabled geologists and archaeologists to map out the movements of both, and to investigate the interrelationships between the two. It has also done much more than can be explored here to increase our understanding of the changing flora, fauna, and climate of North America (and elsewhere) from the time of the glaciers to the present. None of that could have been accomplished without the detailed chronological framework provided by carbon-14.