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CHAPTER 5

THE AGE OF THE EARTH

THE ENORMOUS EXPANSION IN THE TIMESCALE of earth history is one of the more formidable conceptual revolutions produced by modern science. The biblical timescale, based on a literal reading of the creation story in the book of Genesis, places the origin of the earth (and indeed of the whole universe) only a few thousand years ago. In this story, there is no prehistory because human beings are there from the start, and we know something about their activities from the sacred record. Contrast this with the picture established by the modern earth sciences, in which the earth is several billions of years old, with the human species appearing only at the very end of a vast sequence of events. Without this extended timescale, the theory of evolution is unthinkable, and it is no accident that modern "young earth" creationists seek to undermine the plausibility of the worldview established by the earth sciences. The biblical timescale was widely accepted in the late seventeenth century when the first efforts were being made by naturalists to understand the geological and the fossil records. Over a period of a century or more, continued work in this area made it increasingly difficult to sustain a theory of the earth that did not contain an extended sequence of physical events stretching over a vast period of time. Just how vast that period was would remain controversial until the early twentieth century. To the young earth creationists it is still controversial today.

The history of the earth sciences has tended to focus on issues that highlight the supposed "warfare" between science and religion. This has had a distorting effect on our interpretation of the theoretical debates, an effect that has been slowly dispelled by more recent historical studies. The older model of how these sciences developed, still visible in C. G. Gillispie's *Gen-*

esis and Geology (1951), adopted a "heroes and villains" approach in which a few key scientists were identified as the founders of the modern timescale. Those who opposed these pioneers were dismissed as bad scientists who allowed their work to be distorted by their religious beliefs. The two most important heroes were James Hutton and Charles Lyell, who promoted the geological methodology of "uniformitarianism." This method ruled out any appeal to unknown causes and saw the earth's history as an almost eternal cycle of slow, gradual changes. Significantly, Charles Darwin was one of Lyell's greatest disciples. Opposed to uniformitarianism was a geological theory called "catastrophism," which sought to limit the necessity for a vastly extended timescale by invoking violent events in which whole continents could be created or destroyed almost instantaneously. This not only limited the need to challenge the Genesis timescale but also allowed Noah's flood to be seen as a real geological event. Lyell and Hutton were portrayed as the founders of the modern earth sciences, while the catastrophists were ridiculed as religious bigots who manipulated their science to defend narrowly defined religious beliefs.

Modern historians have almost completely overturned this simple black-and-white model of how geology developed. Far from being poor geologists, the catastrophists made major contributions to our understanding of the sequence of geological periods making up the earth's history. They had no interest in reducing the age of the earth to a few thousand years, and most of them had no intention of portraying the last catastrophe as the flood recorded in Genesis. At the opposite end of the scale, it has been shown that Hutton and Lyell had their own religious and cultural values, which significantly influenced their scientific thinking. Although their models of earth history look superficially modern, they contain elements that no modern geologist could accept. Outside the English-speaking world they were largely ignored. The geologists of the late nineteenth century continued to work with a timescale that was much shorter than we accept today, although it was still immense by human standards. Lyell's impact was more on the popular imagination—his books were widely read—than on science. Only in the early twentieth century did new evidence from physics force the geologists to begin working with a timescale extending to billions of years.

Studying the controversies over the age of the earth thus provides us with a good illustration of how the history of science has developed. New insights have been arrived at by challenging the myths established by the scientists themselves (and sometimes by their opponents). The older historiography was based on a tendency to manufacture heroes and villains according to a superficial estimate of how closely their theories approximated to what scientists accept today. And when apparently "bad" science was identified, external forces such as religious beliefs were called in to explain why those involved were deflected from the true path of scientific objectivity. The influence of the heroes was greatly exaggerated, giving the impression that they were able to precipitate a sudden revolution establishing the modern theoretical paradigm. We now see that the whole process was far more protracted and that the emergence of the modern view of earth history required the synthesis of different theoretical and methodological perspectives once thought to be mutually hostile to one another.

Stephen Jay Gould—himself a paleontologist—eloquently captured the need to rethink the conceptual differences between uniformitarians and catastrophists. His *Time's Arrow, Time's Cycle* (1987) shows how Lyell's apparently modern viewpoint rested on a "steady state" view of the past in which the earth could have no beginning and no end. By this standard, the modern view of geological time is more closely related to that of the catastrophists because they saw the earth as a planet that had a beginning and underwent a sequence of developments leading toward the earth we know today. Simply having more time in his theory did not ensure that Lyell got all the rest of his geology right. The catastrophists who resisted his arguments may have had good reasons for doing so, although this does not rule out the possibility that some of their reasons may have come from outside the bounds of science (for other modern surveys of the history of geology, see Greene [1982], Hallam [1983], Laudan [1987], Oldroyd [1996], Porter [1977], and Schneer [1969]).

Seventeenth-Century Theories of the Earth

One consequence of the so-called Scientific Revolution (see chap. 2) was that by the middle decades of the seventeenth century the earth itself became an object of study, and its origins a topic of theoretical speculation. Some of the resulting ideas sound bizarre by modern standards, but they helped to identify issues and problems that would shape the subsequent history of geology. One characteristic of these early theories that seems particularly odd today is the fact that they were almost all shaped within a conceptual framework defined by the biblical timescale. The seventeenth century was the period in which Protestant theologians and scholars established the "young earth" chronology based on a literal reading of Genesis.

(Paradoxically, the Church Fathers who established the foundations of Christian thought in the early centuries did not take the creation story literally.) In the mid-seventeenth century it was James Ussher, archbishop of Armagh, who published the now widely ridiculed calculation that the earth was created in 4004 B.C. His technique established the date of Adam's creation by working back through the Hebrew patriarchs. By taking the seven days of creation literally, it was then only a matter of adding on those seven days to arrive at the date of the creation of the earth and the universe itself. Ussher's scholarship was widely respected at the time and the naturalists who studied the structure of the earth at first saw little reason to challenge it. So their "theories of the earth" were framed in such a way that any changes they postulated could be fitted into this short timescale (see chap. 15, "Science and Religion").

Some of these early theories arose out of efforts to situate the origin of the earth within the new cosmologies proposed by Descartes and Newton (for details, see Greene [1959], Rappaport [1997], and Rossi [1984]). Thomas Burnet's *Sacred Theory of the Earth* (1691) followed Descartes in depicting the earth as a dead star and explained Noah's flood as the consequence of a massive collapse of the originally smooth surface (fig. 5.1). William Whiston's *New Theory of the Earth* (1696) appealed to Newton's theory to explain the flood as a due to water deposited from a near-collision with a comet. Both followed the biblical timescale, although Burnet—whose theory was criticized for departing from the literal text of Genesis—warned against tying the veracity of the sacred record too closely to a single theory. Burnet was aware that there were forces of erosion that could wear away mountain ranges but argued that the continued existence of mountains was evidence that they had been formed quite recently as fragments of the original crust.

What was new about these theories was their willingness to explain events of deep spiritual significance, such as Noah's flood, as a consequence of purely physical events. More disturbing in the long run was the evidence accumulated by naturalists who began to study the structure of the rocks and the fossils they contained. After some debate, it became widely accepted that fossils were the remains of once-living creatures petrified within the rocks (Rudwick 1976). The anatomist Nicholas Steno showed how fossil shark's teeth were almost indistinguishable from those of a living shark he had dissected. Robert Hooke showed that fossil wood was similar to its modern equivalent even under the microscope. Both Steno and Hooke noted the appearance of fossils within layers or strata of rock that gave every appearance of being deposited under water, even though they were now exposed on dry land.

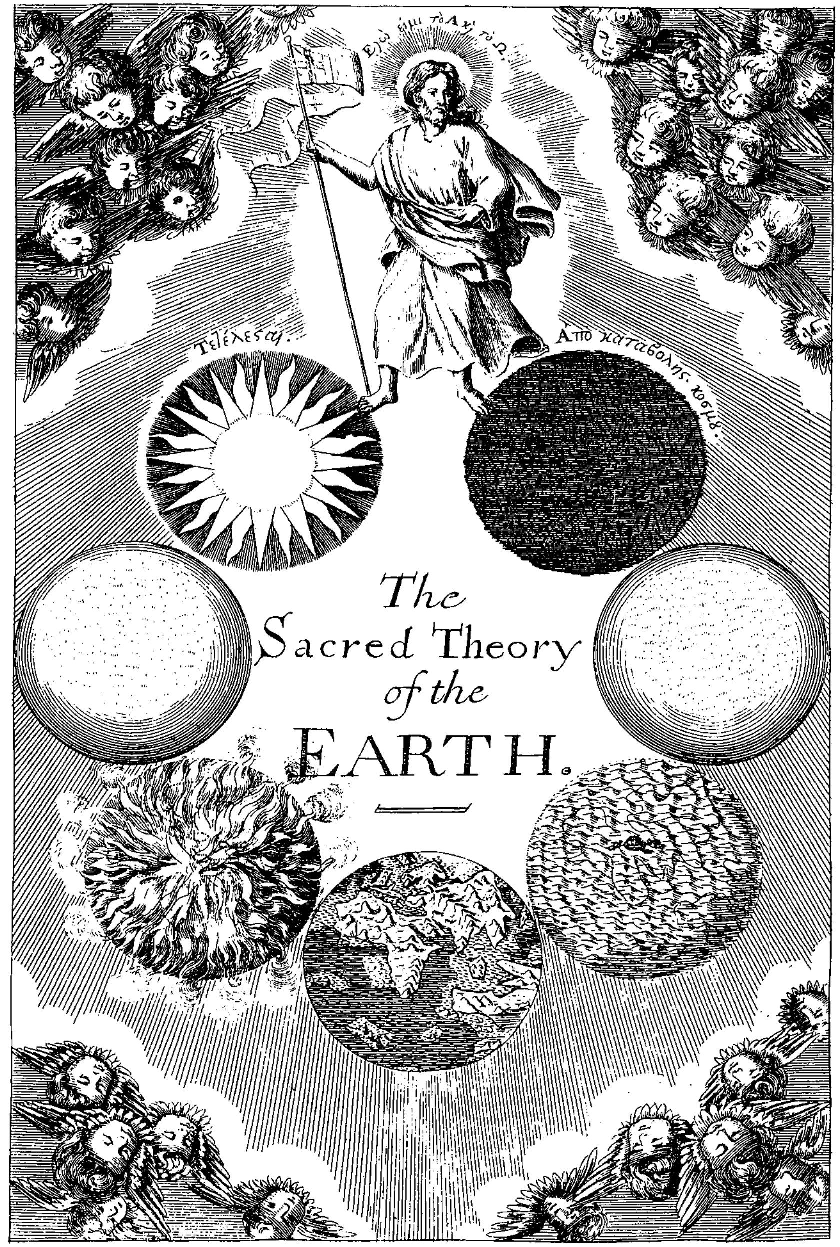

FIGURE 5.1 The frontispiece to Thomas Burnet's *Sacred Theory of the Earth* (1691). Christ stands at the top, astride the beginning and the end of the sequence of events making up the history of the earth. Beginning as a dead star (*top right*) the earth acquires a smooth crust, which then breaks up in Noah's flood—the ark is just visible—to give the irregular surface of today's continents. Eventually, the planet will reignite and become a star again.

One possible explanation for this, expounded by the fossil collector John Woodward in his *Essay toward a Natural History of the Earth* (1695), was that all the sedimentary rocks were laid down from sediment created when Noah's flood covered the whole surface (this is the theory still advocated by young earth creationists). But Steno and Hooke were already aware of problems with this view. The twisting and faulting of the strata gave the strong impression that they had been massively transformed after having been laid down; indeed there seemed to have been a whole sequence of events by which the present structure of earth's surface had been formed. Hooke postulated earthquakes that had raised new areas of land surface from the depths of the ocean. But, unwilling to challenge the short timescale proposed by the theologians, he assumed that these events had been catastrophic. Here we see the origins of the legend that a "catastrophist" position was designed to shorten the timescale by invoking violence rather than gradual processes such as those observed today. Yet Hooke was as interested in the legend of the sinking of Atlantis as he was in the biblical flood. He also noted that some fossils seemed to represent creatures no longer alive today, raising the disturbing prospect that species created by God might have gone extinct in the course of time (fig. 5.2).

Buffon and the Dark Abyss of Time

The worrying implications of these observations were articulated more actively during the eighteenth-century Age of Enlightenment. Philosophers, especially in France, now felt that human reason could hope to understand the nature of the physical universe and humanity's place within it. They were impatient with the Church, which they held to be an agent of social conservatism, and were willing to exploit any avenues offered by science to discredit its teaching. The potential challenge to the Genesis creation story offered by the earth sciences did not go unnoticed. Already in the early years of the new century Benoît de Maillet wrote his *Telliamed*, an account of the earth's history that took it for granted that vast amounts of time had been needed to shape the rock formations we observe. There was no mention of a universal flood—instead de Maillet opted for the increasingly popular retreating-ocean theory, later called "Neptunism" after the Roman god of the sea. He supposed that the whole planet had once been covered with a vast ocean, which had gradually diminished in depth, exposing dry land and the sedimentary fossil-bearing rocks we see today. Far from being an attempt to preserve the credibility of Noah's flood, *Telliamed* pushed the

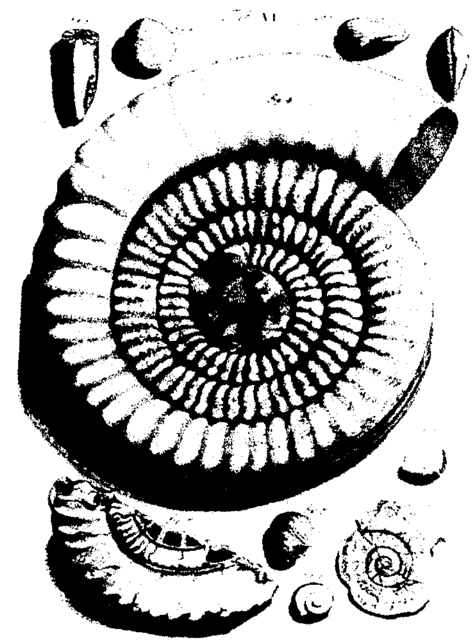

FIGURE 5.2 Fossil ammonite from Robert Hooke's "Lectures and Discourses of Earthquakes," in *The Posthumous Works of Robert Hooke* (London, 1705), plate 6. The plate also shows other common fossil seashells, but Hooke notes in his text that no shell exactly resembling the ammonite is found in the modern seas, raising the possibility that these creatures are now extinct.

great ocean back into the distant past and made no mention of any more recent inundation. Although not published in his own lifetime (it circulated in manuscript) de Maillet still though it prudent to pretend that his non-biblical theory was suggested to him by an Egyptian wise man whose name just happened to be his own, read backward.

The most famous assault on the biblical timescale came from the leading Enlightenment naturalist, Georges Louis Leclerc, comte de Buffon (see Roger 1997). Buffon's *Natural History*, the first three volumes of which appeared in 1749, eventually expanded to become the most comprehensive account of the living world then available. As a follower of Newton, Buffon wanted to explain the origins of the present world in a purely materialist way. His first volumes included a comprehensive theory of the earth from its beginnings to the present. According to Buffon, the best way of explaining the orbits of the planets was to assume that they were all derived from globules of molten material struck off from the sun by a glancing blow by a comet. Each planet, the earth included, then gradually cooled down, and Buffon made observations of how rapidly large bodies cooled after removal from a furnace to estimate how long it might have taken the earth to cool to its present temperature. The answer he reported was 70,000 years, a figure that seems trivial today, but that expanded the old timescale by an order of magnitude. Privately he thought it might be much longer than this, and even he expressed fear at gazing into the "dark abyss of time" (Rossi 1984).

Buffon was censured by the Church authorities and forced to print a retraction of his assault on Genesis. But as superintendent of the Royal Gardens (the modern Jardin des Plantes) in Paris he was relatively secure from persecution, and in 1778 he published a revised version of his theory as a supplementary volume to the *Natural History* with the individual title *The Epochs of Nature.* He still began with his theory of planetary origins but now traced a definite sequence in the events leading from the earth's initial molten state to the present. The only concession to tradition was that there were seven epochs, which could be identified loosely with the seven "days" of creation in Genesis. Buffon's cosmological theory gave his history an obvious "direction" defined by the cooling of the earth. Originally too hot to support life, our planet eventually cooled enough to allow the appearance of species adapted to high temperatures. These died off as the cooling proceeded, to be replaced by the ancestors of the present species. These had been forced to migrate toward the equator as the earth cooled—Buffon pointed to the fossils of "elephants" (we now call them mammoths) as evidence that tropical creatures had once flourished in Siberia.

There was, however, another "direction" built into the theory. Like de Maillet, Buffon could not follow Hooke in his supposition that earthquakes could elevate the land surface. He assumed that once the earth had solidified it was completely rigid. The only way of explaining how sedimentary rocks are now exposed on dry land was to invoke the retreating ocean theory (although for Buffon the ancient ocean had at first been boiling hot). Once dry land appeared, however, it was attacked by wind, rain, frost, and the other agents of erosion, which wore down the surface. The debris was washed down rivers and into the sea, where the sediment was laid down to form younger rocks on top of those deposited while the whole earth was covered in water. In this respect, Buffon anticipated the most important techniques exploited by the geologists of the late eighteenth century. But

he made little progress in identifying the sequence of rock formations, and his theory remained embedded in an older tradition in which theories of the earth took their origins from cosmological speculation.

Stratigraphy and the Fossil Record

The empirical study of rocks, minerals, and fossils had not been just a matter of curiosity. In an age where Francis Bacon's philosophy had been used to promote the claim that science would allow us to control nature by understanding its operations, the study of the earth's surface had obvious potential benefits to the mining industry. If we could know which rocks held the best prospect of yielding useful minerals, the economic benefits would be enormous. By the late eighteenth century, this pragmatic approach to the study of the earth had become well established in Germany, where many of the small independent states drew their income from mining. Mining academies were set up to train people in the skills needed to locate and extract minerals, and here the practical implications of a detailed knowledge of the earth's crust first became apparent. Out of this practical study of minerals came a methodology for identifying the sequence in which the successive rocks had been deposited in the course of the earth's history. This was the science of stratigraphy, based on the principle of superposition, that is, the assumption that newer rocks were always laid down on top of existing rocks. The assumption was necessarily historical because the identification of a rock's position in the sequence of deposits implied identifying the period in the earth's history when it was laid down. From the early efforts to define the sequence of formations (and hence the sequence of geological periods) came the modern outline of the earth's history.

In its earliest version, this program was associated with the name of Abraham Gottlob Werner, who taught at the mining school in Freiburg. Although he published little, Werner attracted students from all over the world and thus achieved immense influence. He concentrated on identifying the mineral character of rocks and then assumed that each type of rock was laid down at a particular period in the earth's history. He felt justified in making this assumption because he accepted the Neptunist theory—as the great ancient ocean dried up, the chemicals in it were precipitated out in a particular sequence. Eventually, erosion of the land surface would add a regular sequence of sedimentary rocks.

Although this theory was widely accepted in the late eighteenth century, it was soon refuted by evidence that the same types of rocks can be laid down at different periods of history. Later scientists ridiculed Werner and expressed astonishment that anyone could be taken in by so obviously false a theory. Because some of Werner's followers tried to link the theory with a reemergence of the waters that could be identified with the biblical flood, it was argued that Neptunism was bad science maintained by those with an interest in defending religion against materialism. It is certainly true that some Neptunists, including Richard Kirwan and Jean-André Deluc, tried to link the theory with the flood. These were conservative thinkers who, in the aftermath of the French Revolution, wanted to make sure that the New Science did not endorse an assault on the Church as a bastion of the social order. But such attitudes were largely confined to Britain. Werner himself expressed no interest in the Genesis story, nor did his Continental followers. They followed the theory because it offered hope of providing an ordering principle by which the complex sequence of rock formations could be understood. If they oversimplified in their anxiety to make order out of apparent chaos, they nevertheless conceived the basic program by which geology would advance, that is, the program of identifying the rock formations by the order in which they were laid down. And because the sequence was a long one, there was no question of it being compressed within the biblical timescale.

By the early nineteenth century, it was becoming clear that the Neptunist theory could not be sustained. The famed traveler Alexander von Humboldt saw for himself the immense power of volcanoes and earth movements when he studied the Andes Mountains in South America. Humboldt and many others abandoned Neptunism, but they continued to regard themselves as followers of Werner because they saw their key task as the identification of the successive rock formations. It was Humboldt who named the Jurassic formation, after characteristic rocks found in the Jura Mountains on the French-Swiss border. Earth movements replaced the retreating ocean as an explanation of how the sedimentary rocks were elevated to form dry land.

It was now recognized that since similar rocks could be formed at different periods in the earth's history, the best way of identifying the sequence was through the fossils embedded in the strata. The fossils of each period were characteristic, whatever the type of rock they were embedded in. Stratigraphy was firmly linked to the establishment of a series of geological periods, each of which was assumed to have its own population of animals and plants quite unlike those that are alive today (fig. 5.3). The fossil-based stratigraphy was pioneered in England by the canal-builder William Smith

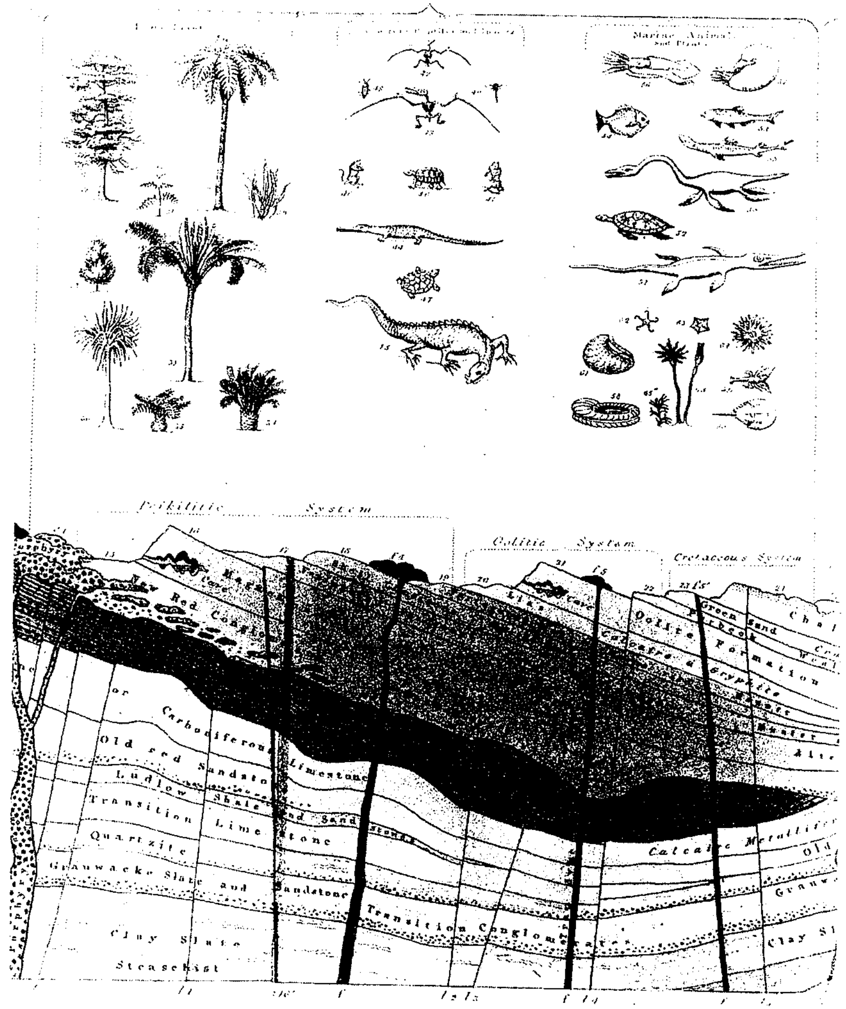

FIGURE 5.3 Part of a hypothetical cross section of the earth's crust from William Buckland's *Geology and Mineralogy Considered with Reference to Natural Theology* (London, 1837), vol. 2, plate 1. The cross section shows beds of sedimentary rocks distorted by later earth movement and with veins of igneous (volcanic) rock intruding from below. The figures at the top show creatures typically found as fossils in the Secondary rocks (the Mesozoic era) including a dinosaur looking remarkably like a dragon. Compare this with fig. 5.5 below.

and in France by the paleontologist Georges Cuvier and the geologist Alexandre Brongniart. Historians of geology still debate the relative significance of their contributions: Smith's geological map of England and Wales of 1815 was a pioneering work, but he was to some extent marginalized by the elite scientists of the time. Cuvier was at the heart of the French scientific establishment, a leading figure in the creation of comparative anatomy and the reconstruction of vertebrate fossils. He studied the structure of different species of animals in order to work out the underlying principles on which the different types of organization were based, and he used his skills to put together the often-fragmentary bones being dug out from the rocks all over Europe. It was Cuvier who established the reality of extinction beyond all reasonable doubt—no one could believe that the mammoths and mastodons he described were still alive in some remote part of the world. From this point on, scientists could take it for granted that each new formation would have distinctive fossils of its own, many of the earlier species having died out and been replaced. But it was Brongniart's work with the fossil invertebrates that proved the more useful guide in establishing the sequence of rocks, as in their collaborative survey of the formations making up the Paris basin, published in 1811.

Over the next couple of decades, geologists extended the sequence of formations down to the oldest fossil-bearing rocks (fig. 5.4). It was in Britain that some of the oldest and hence most distorted formations were sorted out. Working in Wales, Adam Sedgwick and Roderick Impey Murchison named the Cambrian and Silurian systems, respectively (significantly, Darwin got his first geological training on a field trip with Sedgwick). In 1841 John Phillips named the three great eras in the history of life: Paleozoic, Mesozoic, and Cenozoic (the eras of ancient, middle, and new life). The Mesozoic was already becoming known as the "age of reptiles" thanks to the discovery of dinosaurs and other extinct reptile species (fig. 5.5), although it was again the invertebrate fossils that formed the basis of the technical classification. Defining the boundaries between the systems was far from straightforward and required a good deal of negotiation between experts. Sedgwick and Murchison fell out over the Cambrian-Silurian boundary, while the overlying Devonian also caused a great deal of controversy (see Rudwick [1985] and Secord [1986] on these debates). Yet by the 1830s, no one could ignore the fact that the earth's crust was composed of a vast series of deposits, each of which represented a whole epoch of geological time. As yet no one would hazard an estimate of just what length of time was involved, but clearly the amount was immense by the standards of human history.

	Modern names	Old names (c. 1850)	
Cenozoic era (Age of mammals)	Recent	Recent deposits	Tertiary series
	Pleistocene		
	Pliocene	Pliocene	
	Miocene	Miocene	
	Oligocene		
	Eocene	Eocene	
	Paleocene		
Mesozoic era (Age of reptiles)	Cretaceous	Cretaceous	Secondary series
	Jurassic	Wealden	
		Oolitic	
		Lias	
	Triassic	New Red Sandstone	
Paleozoic era (Age of fishes and invertebrates)	Permian		Transition series
	Carboniferous (Pennsylvanian Mississippian)	Carboniferous	
	Devonian	Old Red Sandstone	
	Silurian	Silurian	
	Ordovician		
	Cambrian	Cambrian	
	Precambrian	Primary rocks	

FIGURE 5.4 The sequence of geological formations established by the mid-nineteenth century (*right*) and their modern equivalents. The sequence of formations corresponds to the succession of geological periods in the earth's history. The complete sequence is never observed in any one location but is built up by using fossils and other clues to identify rocks of the same age in different areas.

Catastrophism and Uniformitarianism

Cuvier noticed that the boundaries between successive formations seemed abrupt, so that the transition from one fossil population to the next appeared to have been more or less instantaneous. In his *Discourse on the Revolutions of the Surface of the Globe,* first published in 1812 as the introduction to his survey of fossil vertebrates, he attributed the sudden extinction of species to catastrophic earth movements and tidal waves. There did seem to be a lot of evidence for a dramatic transformation of the landscape in the re-

FIGURE 5.5 Life-sized reconstruction of the carnivorous dinosaur *Megalosaurus*, originally described by William Buckland. Richard Owen, who created the name "dinosaur," helped to design this and other models in the 1850s. They can still be seen at Crystal Palace in Sydenham, south London. The dinosaur is depicted as a giant lizard walking on four legs, although later discoveries of more complete fossils showed that *Megalosaurus* actually walked on its hind limbs.

cent geological past. Vast mounds of boulder-clay, and gravel, along with large "erratic" boulders, littered the landscape of northern Europe. There was no observable cause that could have transported this material across the face of the earth, so it seemed natural to postulate a great flood. Cuvier made no effort to identify this last catastrophe with the biblical deluge, but his British followers had no such qualms. William Buckland, the reader in geology at the fiercely conservative University of Oxford, sought to vindicate his science from the charge that it aided irreligion by showing how it could provide evidence that Noah's flood was a real event. His *Reliquiae diluvianae* [*Relics of the Flood*—only the title was in Latin] of 1823 described a cave at Kirkdale in Yorkshire that had been filled with mud, in which was buried the bones of hyenas and their prey (fig. 5.6). How else except by a universal flood could a cave in the hills have been filled in this way? And the event seemed to have been accompanied by major transformation of the climate, since hyenas are no longer to be found in Europe. For Buckland this was evidence of a geological catastrophe that would fit in with the Genesis record.

Older histories of geology describe this theory of "catastrophism" as a disaster for the development of the science. Wildly improbable events, possibly of a miraculous nature, were postulated to make the theory fit into a preconceived model defined by Genesis. By invoking violent events as agents of transformation, the need to extend the age of the earth much beyond the traditional estimates was avoided. On this model, catastrophism is a classic example of the kind of bad science that is done when external forces such as religion interfere with scientific objectivity. The rival uniformitarian model of Hutton and Lyell (discussed below) showed the real way forward through the study of observable causes and the postulation of vast amounts of time in which they could have transformed the earth.

The uniformitarians' model of the history of geology has now been profoundly modified if not rejected outright. It is a vision of the science's

FIGURE 5.6 Cross section through a cave similar to the one described by William Buckland at Kirkdale in Yorkshire, northern England, from Buckland, *Reliquiae diluvianae* (London, 1824), plate 27. The cave is partially filled with hardened mud containing the remains of animals of kinds no longer found in Europe. Buckland argued that a global flood was the only explanation of how caves like this, well above sea level, could have been filled with mud. The material is now thought to have come from lakes formed when valleys were dammed by glaciers during the ice age.

history first sketched in by Lyell himself—and he was hardly an objective scholar on this topic. Lyell insisted that both Neptunism and catastrophism were implausible theories supported solely for nonscientific (i.e. religious) reasons. Modern studies reveal how distorted this condemnation is. We have seen how catastrophist geologists such as Cuvier, Humboldt, Sedgwick, and Murchison played key roles in establishing the stratigraphical sequence still accepted today. Most Neptunists and catastrophists had no interest in linking their theories to the flood story—only a few conservative writers in the English-speaking world followed this line. Cuvier went out of his way to insist that the last catastrophe was not universal, as Genesis implies, and even Buckland eventually gave way on this point. For all of them, the most recent catastrophe was only the last in a vast sequence of violent transformations, all separated by periods of relatively normal conditions. All the earlier periods lay completely outside the biblical story of creation. There was good evidence that something anomalous had happened in the recent geological past, and the uniformitarians struggled to explain the mud deposits studied by Buckland and related phenomena. Only in the 1840s was it suggested that this material might have been transported by glaciers in an "Ice Age" when much of northern Europe had been buried in ice, and this theory took several decades to gain wide acceptance (Hallam 1983).

There was another factor that made catastrophism plausible and that incidentally made geologists reluctant to accept a cold spell in the past. Lyell did his best to imply that the catastrophists invoked supernatural causes (miracles) to explain their hypothetical upheavals. But they had no intention of appealing to anything but natural causes—they just thought there was evidence that earthquakes had once occurred on a scale far beyond anything we have observed in the few thousand years of recorded human history. In fact, the catastrophists relied on the assumption that the earth's history is much vaster than human history to argue that what little we have observed is not necessarily typical of the whole. Their theory also had a sound basis in physics. Everyone now accepted that the center of the earth was very hot. This explains the origin of the molten rock expelled by volcanoes, and the concept of a reservoir of molten or at least very hot rock, under enormous pressures, deep in the earth also seemed to explain the instability of the solid crust revealed by earthquakes. If the center of the earth is hot, however, both common sense and the physicists' studies of the behavior of hot bodies suggest that it must cool down. Heat will be conducted up to the surface (or brought up by molten lava) and radiated into space.

The early nineteenth century thus saw a reinvigoration of Buffon's cooling-earth theory.

The implications for the cooling-earth theory for catastrophism were explored by geologists such as Léonce Elie de Beaumont. If the central heat of the earth diminishes, then volcanic activity would also be expected to diminish in the course of geological time. More significant, earthquake activity would diminish as the crust got thicker and the rate of cooling slowed down. An analogy suggested by Constant Prévost compared the earth with the wrinkling of an apple: the skin wrinkles because its surface area remains constant while the volume of the apple is reduced by evaporation. A cooling earth would also diminish in volume, so mountain building will be caused by a similar crumpling of the skin. But as Elie de Beaumont pointed out, the earth's crust is rigid, so the crumpling will be expected to take place in sudden catastrophic events when the pressures building up beneath finally cause the crust to give way. Since the planet was hotter in the past, it was natural to assume that past episodes of mountain building involved earth movements on a scale far beyond anything observed in the modern world. The cooling-earth theory thus provided catastrophism with a plausible physical mechanism to complement the evidence geologists had for discontinuities in the past.

The uniformitarian alternative to this model has been hailed as the foundation stone of modern geology because it adopts a methodological precept based on the claim that a true science operates only with those causes it can actually observe. In fact, the catastrophists were quite happy with this method of "actualism" because their upheavals were supposed to be the same as modern earthquakes only bigger. But to uniformitarians, only observable causes acting at observable intensities can be employed by a truly scientific geology. Anything else opens up the way to wild speculation and even the postulation of supernatural causes. This was the methodology pioneered by James Hutton and articulated most fully by Charles Lyell in the 1830s. It seems very modern because our current geological theories include little room for catastrophes (although asteroid impacts are now widely accepted to have interrupted the steady changes produced by internal processes linked to continental drift). The uniformitarian approach also seems modern in its appeal to vast periods of time. Because all past changes, including the elevation of mountain ranges and the excavation of valleys, are to be explained by modern-scale earth movements and erosion, vast amounts of time are needed for such slow-acting agents to produce the effects we observe. It would be quite wrong to accuse the catastrophists of opting for a young earth along the lines proposed by Archbishop Ussher, but there is no doubt that the demands made by uniformitarians for an extension to the timescale went far beyond anything that had been imagined before.

The uniformitarian method was not without its problems, however. In their anxiety to rule out speculation, the uniformitarians were forced to opt for what Gould (1987) calls a "cyclic" model of earth history. There can be no arrow of time defined by cooling or the retreating ocean—past geological periods have seen only an eternal cycle of events similar to those we observe today. It is outside the realm of science to postulate a period when things were radically different—let alone a process by which the planet itself was given its modern form. These are restrictions that no geologist could accept today, so the claim that uniformitarianism forms the sole basis of our modern science is flawed. Modern geology draws on both the uniformitarian and the "directionalist" model of the catastrophists. Once we realize this, we see that neither side in the debate should be presented as "pure" scientists working only on objective principles. It is as important to know why Hutton and Lyell were motivated to propose a steady state theory of the earth as it is to know why some catastrophists were tempted by biblical ideas about the flood.

The first effort to put this program into operation was made by the Scottish geologist James Hutton (Dean 1992). In a paper published in 1788, and again in his two-volume *Theory of the Earth* of 1795, Hutton took on the Wernerianism promoted in his native Edinburgh by Robert Jameson. Hutton dismissed the retreating ocean theory by pointing out (as Hooke had done a century earlier) that earth movements could explain how the sediment laid down on the seabed could be elevated to dry land. He could draw on studies of volcanoes that had begun to suggest that they derived their lava from reservoirs of molten rock deep in the earth. The idea that the earth's central heat was responsible for most geological activity came to be known as "Vulcanism" after the Roman god of fire. Hutton linked this theory with his belief that the earth's crust was unstable—for him it was the central heat that was responsible not only for volcanoes but also for earth movements and mountain building. He also argued that many of the so-called primary rocks, including granite, were of igneous origin: they had crystallized out from a molten state, not from solution in water. When challenged to explain why these rocks look so different from the lavas expelled by modern volcanoes, he showed how molten rock could intrude between the strata deep in the earth and there cool very slowly. This gave time for the crystals seen in rocks such as granite to form. For Hutton, granite

could be produced at various points in the earth's history—it was not necessarily the most ancient of rocks as the Wernerians had claimed.

What made Hutton's theory different from any other form of Vulcanism was his insistence that the processes responsible for forming the rocks have all occurred at the same rate as we observe today. Although it was hot inside, the earth was not cooling down, so earth movements were not diminishing in intensity. Hutton also went to great lengths to show how the ordinary agents of erosion—wind, rain, flowing streams, and so on—can have sculpted out the valleys within mountain ranges. There was no need to postulate violent tidal waves, provided one allowed for the vast amounts of time needed for a flowing stream to carve its own valley through the mountain rocks. The debris from this erosion was washed out to the seabed, where it was laid down as sediment, baked into rock, then eventually elevated to produce more dry land. There was a perfect cycle here, in which the elevation of new land exactly balanced the destruction of the old surface by erosion. Hutton was accused of being irreligious by conservative Wernerians because his theory had no room for a flood and demanded vast amounts of time. More seriously, from the conservative point of view, it had no room for a creation: Hutton's earth was eternal, a perpetual motion machine that never ran down. He wrote that "we find no vestige of a beginning—no prospect of an end" (Hutton 1795, 1:200) Yet in fact, Hutton's motivation for setting up such a theory was his own religious beliefs, which were deist rather than Christian. His god was the perfect workman who had designed a machine that could work forever without His superintendence. The purpose of the whole system was to maintain the earth as a habitat for living things because without the perpetual rebuilding of the land surface all the soil on which life depends would eventually be washed out to sea.

Hutton's theory generated controversy in Edinburgh but attracted little attention elsewhere. It was more widely disseminated by John Playfair's *Illustrations of the Huttonian Theory* of 1802. In Britain, at least, his work played a role in the conversion of geologists from Neptunism to Vulcanism—but it was the catastrophist version of Vulcanism based on the cooling-earth theory that benefited. Continental geologists had their own reasons for moving toward catastrophism. The uniformitarian model was eventually revived in Charles Lyell's *Principles of Geology* (1830–33) as the basis for an explicit attack on catastrophism (Wilson [1972], but see also Rudwick's introduction to the modern reprint of the *Principles*). It was the introductory historical chapters of the *Principles* that created the negative image of both Neptunism and catastrophism accepted by later scientists. Lyell's assault was explicitly methodological, accusing the catastrophists of betraying science by opting for wild speculation rather than careful observation. His book played an important role by providing evidence of just how much change is actually occurring through the action of modern volcanoes, earthquakes, and erosion (fig. 5.7). Lyell had studied Mount Etna in Sicily and had shown how this immense volcano had been built up from a vast series of eruptions, only the last few of which had been witnessed by humans. It was ancient by human standards, yet it stood on the youngest sedimentary rocks. Lyell dismissed all the so-called evidence for catastrophes in the past as illusory: it was always possible to imagine a long sequence of ordinary changes that could have produced the effect, given enough time. The apparently sudden transitions from one stratum to another were the result of vast periods being unrepresented in the sedimentary record. Lyell made his own contribution to stratigraphy by naming the Eocene, Miocene, and Pliocene formations—but he showed that the fossil populations did not completely change from one to the other. There were always some species that survived, undermining the plausibility of catastrophic extinctions.

Although he accepted the conventional sequence of geological formations, Lyell had revived Hutton's cyclic or steady state model of history. He assumed that even the earliest strata we see had been formed under conditions essentially similar to those of today. The known geological record is only the last part of an endless sequence, all the earliest phases of which have been destroyed or distorted beyond recognition. Science cannot hope to find evidence of a "primitive" phase of earth history dating from the planet's purely hypothetical formation. To maintain his steady state theory, Lyell attacked the evidence used to support the cooling of the earth, arguing that there had been only a fluctuation in the climate as continents were created and destroyed. He also insisted that the apparent progressive development of life was an illusion—eventually we would find mammalian fossils in even the oldest rocks. Here we see the ways in which Lyell's position went far beyond what geologists can accept today. In effect, his methodology became a straightjacket confining him to an ahistorical view of the earth. His position can to some extent be linked to his religious and political beliefs. Lyell was a liberal in politics, and he resented the way in which conservatives like Buckland were using catastrophism to defend Christianity and by implication the Church as pillars of aristocratic privilege. His own religious beliefs—so strongly held that he could never accept Darwin's view of human origins—were more like Hutton's, a form of deism in which a wise and benevolent Creator has designed a universe that can operate for ever without renewal.

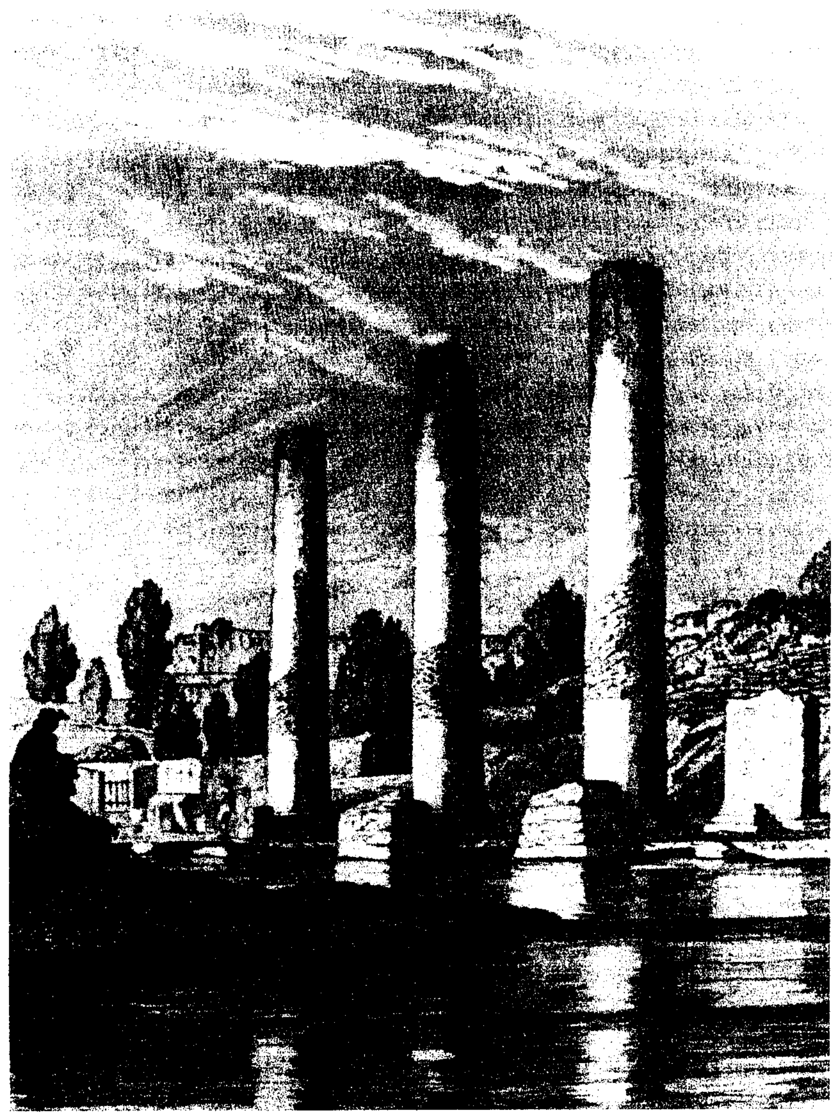

FIGURE 5.7 The Roman temple of Serapis at Puzzuoli, outside Naples, the frontispiece to Charles Lyell, *Principles of Geology* (London, 1830–33), vol. 1. The dark bands on the columns have been formed by the action of marine creatures, showing that earth movements have submerged the temple beneath the sea and then elevated it again but without actually destroying the columns. Lyell argued that if noncatastrophic earth movements could have this much effect in the two thousand years since Roman times, over a longer time span they could elevate mountain ranges or even whole continents.

Lyell was a popular writer and was influential in convincing the general public that the earth was immensely old. His impact on geology is more debatable. His greatest disciple was Charles Darwin, who saw evidence on his voyage aboard HMS *Beagle* that the Andes Mountains were still being elevated by earthquakes. Darwin applied the uniformitarian method where Lyell would not: to the organic world and the process by which species change in the course of time (see chap. 6, "The Darwinian Revolution"). But even he would not follow Lyell in his rejection of the progressive development of life. Most geologists acknowledged the power of modern causes and scaled down the catastrophes they postulated in the distant past. But they continued to believe that there were episodes of mountain building in which earth movements were much more intensive than we see today. These form the natural "punctuation marks" allowing us to define the geological periods (for Lyell these were merely gaps in the record that we use for convenience). More seriously, most geologists continued to support the cooling-earth theory, seeing this as an essential foundation to explain the crumpling of the crust and the violence of at least some past events. They also tended to limit the age of the earth to around a hundred million years—a vast period by any human standard but far less than Lyell and Darwin wanted and far less than we accept today.

Physics and the Age of the Earth

This last point leads us to a final controversy but one whose significance has often been overestimated. Lyell's steady state theory had a fatal inconsistency: it assumed that the center of the earth is hot, yet it denied that the planet cools down in the course of almost endless geological time. This point was noted in the controversies of the 1830s, but it became crucial as the physicists began to refine their ideas on energy and create the science of thermodynamics (see chap. 4, "The Conservation of Energy"). In the 1860s, the physicist William Thomson, later Lord Kelvin, began to attack Lyell and, by implication, Darwin (Burchfield 1975). In Kelvin's worldview, God had created only so much energy, and as it became slowly less available, the universe was inevitably running down. The cooling of hot bodies was the most obvious expression of this irreversible process, and to Kelvin it was unthinkable that the earth could be treated as an exception. A hot earth must cool down, so Lyell was wrong and the catastrophists right—geological processes must have gone on more rapidly in the past when the earth's interior was hotter. Kelvin then did some calculations to suggest how much time it would have taken an initially molten earth to cool down

to the state in which we see it today. The answer came out to at the most a few hundred million years, far less than Lyell and Darwin were demanding.

It has often been assumed that this assault by the more fundamental science of physics came as a blow to the geologists of the time. But this assumption is based on the mistaken belief that all of the geologists had followed Lyell's uniformitarianism. Kelvin's attack was certainly important for Lyell and for Darwin and the evolutionists. But in fact most geologists were perfectly happy with Kelvin's timescale, indeed they had estimates of their own, based on the rate of sedimentation and on the accumulation of salt in the oceans, which limited the age of the earth to a hundred million years. It was only when Kelvin reduced his estimate to twenty-five million years that the geologists began to complain that the physicists were getting too big for their boots and must have got something wrong. There was simply no way that the convoluted history of the earth revealed by the rocks could be fit into so short a time.

The physicists had got something wrong, of course, and this was already apparent by the end of the century. Radioactivity was discovered in 1896, and its implications soon began to overturn Kelvin's whole worldview (see chap. 11, "Twentieth-Century Physics"). By 1903, Pierre Curie had noted that radioactive elements give off heat, and three years later Lord Rayleigh pointed out that since such elements are distributed throughout the earth in small but significant quantities, a substantial amount of heat would be generated in the interior. This would be more than enough to offset the cooling predicted by Kelvin. Moreover, the rate of radioactive decay of some natural elements is so slow that this source of heat could last for billions of years. In a sense, Lyell was vindicated, since the evidence for radioactive heating now more or less required geologists to extend their timescale enormously and made catastrophes superfluous. Indeed, the new physics precipitated a crisis in the earth sciences by undermining the idea that mountain building was due to the crumpling of the crust on a gradually shrinking earth. This would eventually lead to the postulation of the theory of continental drift and modern plate tectonics (see chap. 10, "Continental Drift").

Radioactivity also provided something that the geologists had always lacked, a way of measuring geological time in absolute terms (as opposed to the relative sequencing of formations). Since the decay products of each radioactive element are known, it is possible to compare the proportion of the original element and its decay product in a mineral and—knowing the half-life (a measure of the rate of decay)—to calculate how old the mineral is. The first technique used the decay of radium to lead, although others such as the potassium-argon method eventually became better known. Within a few years, pioneers of radioactive dating such as Arthur Holmes were estimating the age of the earth to be several billions of years (Lewis 2000). The consensus eventually established the age as around 4.5 billion years, a figure that has remained secure despite numerous refinements through the twentieth century and into the twenty-first.

Conclusions

Geologists have become used to dealing with periods of time that beggar the imagination. Modern young-earth creationists reject the latest figures and dismiss radioactive dating along with the whole apparatus of the modern earth sciences. For them, as for the naturalists of the late seventeenth century, the earth is only a few thousand years old and all the fossil-bearing rocks were laid down beneath the waters of Noah's flood. Nothing could more strikingly indicate the extent of the conceptual revolution involved in scientists' efforts to provide the earth with a history. The full extent of this revolution only became apparent with the emergence of radioactive dating shortly after 1900, although Lyell had made an important effort to extend the timescale to this order of magnitude in the 1830s. In another sense, however, we can see that the main leap of the imagination had already been made before Lyell published. The Neptunist and catastrophist geologists who created modern stratigraphy in the decades around 1800 had already accepted a sequence of geological periods that they know extended into an antiquity far exceeding that of human history. They would not have advertised the age of a hundred million years accepted by their later followers, but they were probably aware that something of this order of magnitude was required. To this extent, the modern concept of geological time had already taken shape, even though it would take the efforts of Lyell and the atomic physicists to complete the final extension of the timescale to the figure we accept today.

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