At the western edge of Death Valley, there are great convex mountain faces that are called turtlebacks. To me they are more suggestive of whales. You look at them and you see that they were once plastically deformed. I think the mountains have tilted up enough there to be giving us a peek at the original bottom of a block. Death Valley is below sea level. I would bet that if we could scrape away six thousand feet of gravel from these mile-high basins up here what we would see at the base of these mountains would look like the edge of Death Valley. I haven't published this hypothesis. I think it sounds right. I haven't done any field work in Death Valley. I was just lucky enough to be there in 1961 with the guy who first mapped the geology. I have been lucky all through the years to work in the Basin and Range. The Basin and Range impresses me in terms of geology as does no other place in North America. It's not at all easy, anywhere in the province, to say just what happened and when. Range after range—it is mysterious to me. A lot of geology is mysterious to me."

Interstate 80, in its complete traverse of the North American continent, goes through much open space and three tunnels. As it happens, one tunnel passes through young rock, another through middle-aged rock, and the third through rock that is fairly old, at least with respect to the rock now on earth which has not long since been recycled. At Green River, Wyoming, the road goes under a remnant of the bed of a good-sized Cenozoic lake. The tunnel through Yerba Buena Island, in San Francisco Bay, is in sandstones and shales of the Mesozoic. And in Carlin Canyon, in Nevada, the road makes a neat pair of holes in Paleozoic rock. This all but leaves the false impression that an academic geologist chose the sites —and now, as we approached the tunnel at Carlin Canyon, Deffeyes became so evidently excited that one might have thought he had done so himself. "Yewee zink bogawa!" he said as the pickup rounded a curve and the tunnel appeared in view. I glanced at him, and then followed his gaze to the slope above the tunnel, and failed to see there in the junipers and the rubble what it was that could cause this professor to break out in such language. He did not slow up. He had been here before. He drove through the westbound tube, came out into daylight, and, pointing to the right, said, "Shazam!" He stopped on the shoulder, and we admired the scene. The Humboldt River, blue and full, was flowing toward us, with panes of white ice at its edges, sage and green meadow beside it, and dry russet uplands rising behind. I said I thought that was lovely. He said yes, it was lovely indeed, it was one of the loveliest angular unconformities I was ever likely to see.

The river turned in our direction after bending by a wall of its canyon, and the wall had eroded so unevenly that a prominent remnant now stood on its own as a steep six-hundred-foot hill. It made a mammary silhouette against the sky. My mind worked its way through that image, but still I was not seeing what Deffeyes was seeing. Finally, I took it in. More junipers and rubble and minor creases of erosion had helped withhold the story from my eye. The hill, structurally, consisted of two distinct rock formations, awry to each other, awry to the gyroscope of

the earth—just stuck together there like two artistic impulses in a pointedly haphazard collage. Both formations were of stratified rock, sedimentary rock, put down originally in and beside the sea, where they had lain, initially, flat. But now the strata of the upper part of the hill were dipping more than sixty degrees, and the strata of the lower part of the hill were standing almost straight up on end. It was as if, through an error in demolition, one urban building had collapsed upon another. In order to account for that hillside, Deffeyes was saying, you had to build a mountain range, destroy it, and then build a second set of mountains in the same place, and then for the most part destroy them. You would first have had the rock of the lower strata lying flat—a conglomerate with small bright pebbles like effervescent bubbles in a matrix red as wine. Then the forces that had compressed the region and produced mountains would have tilted the red conglomerate, not to the vertical, where it stood now, but to something like forty-five degrees. That mountain range wore away —from peaks to hills to nubbins and on down to nothing much but a horizontal line, the bevelled surface of slanting strata, eventually covered by a sea. In the water, the new sediment of the upper formation would have accumulated gradually upon that surface, and, later, the forces building a fresh mountain range would have shoved, lifted, and rotated the whole package to something close to its present position, with its lower strata nearly vertical and its upper strata aslant. Here in Carlin Canyon, basin-and-range faulting, when it eventually came along, had not much affected the local structure, further tilting the package only two or three degrees.

Clearly, if you were going to change a scene, and change it again and again, you would need adequate time. To make the rock of that lower formation and then tilt it up and wear it down and deposit sediment on it to form the rock above would require an immense quantity of time, an amount that was expressed in the clean, sharp line that divided the formations—the angular unconformity itself. You could place a finger on that line and touch forty million years. The lower formation, called Tonka, formed in middle Mississippian time. The upper formation, called Strathearn, was deposited forty million years afterward, in late Pennsylvanian time. Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, Permian, Triassic, Jurassic, Cretaceous, Paleocene, Eocene, Oligocene, Miocene, Pliocene, Pleistocene . . . In the long roll call of the geologic systems and series, those formations—those discrete depositional events, those forty million years—were next-door neighbors on the scale of time. The rock of the lower half of that hill dated to three hundred and thirty million years ago, in the Mississip-

pian, and the rock above the unconformity dated to two hundred and ninety million years ago, in the Pennsylvanian. If you were to lift your arms and spread them wide and hold them straight out to either side and think of the distance from fingertips to fingertips as representing the earth's entire history, then you would have all the principal events in that hillside in the middle of the palm of one hand.

It was an angular unconformity in Scotland—exposed in a riverbank at Jedburgh, near the border, exposed as well in a wave-scoured headland where the Lammermuir Hills intersect the North Sea—that helped to bring the history of the earth, as people had understood it, out of theological metaphor and into the perspectives of actual time. This happened toward the end of the eighteenth century, signalling a revolution that would be quieter, slower, and of another order than the ones that were contemporary in America and France. According to conventional wisdom at the time, the earth was between five thousand and six thousand years old. An Irish archbishop (James Ussher), counting generations in his favorite book, figured this out in the century before. Ussher actually dated the earth, saying that it was created in 4004 B.C. The Irish, as any Oxbridge don would know, are imprecise, and shortly after the publication of Ussher's *Annales Veteris et Novi Testamenti* the Vice-Chancellor of Cambridge University bestirred himself to refine the calculations. He confirmed the year. The Holy Trinity had indeed created the earth in 4004 B.C.—and they had done so, reported the Vice-Chancellor, on October 26th, at 9 A.M. His name was Lightfoot. Geologists today will give parties on the twenty-sixth of October. Some of these parties begin on the twenty-fifth and end at nine in the morning.

It was also conventional wisdom toward the end of the eighteenth century that sedimentary rock had been laid down in Noah's Flood. Marine fossils in mountains were creatures that had got there during the Flood. To be sure, not everyone had always believed this. Leonardo, for example, had noticed fossil clams in the Apennines and, taking into account the distance to the Adriatic Sea, had said, in effect, that it must have been a talented clam that could travel a hundred miles in forty days. Herodotus had seen the Nile Delta—and he had seen in its accumulation unguessable millennia. G. L. L. de Buffon, in 1749 (the year of *Tom Jones*), began publishing his forty-four-volume *Histoire Naturelle*, in which he said that the earth had emerged hot from the sun seventy-five thousand years before. There had been, in short, assorted versions of the Big Picture. But the scientific hypothesis that overwhelmingly prevailed at the time of Bunker Hill was neptunism—the aqueous origins of the visible world. Neptunism had become

a systematized physiognomy of the earth, carried forward to the *n*th degree by a German academic mineralogist who published very little but whose teaching was so renowned that his interpretation of the earth was taught as received fact at Oxford and Cambridge, Turin and Leyden, Harvard, Princeton, and Yale. His name was Abraham Gottlob Werner. He taught at Freiberg Mining Academy. He had never been outside Saxony. Extrapolation was his means of world travel. He believed in "universal formations." The rock of Saxony was, beyond a doubt, by extension the rock of Peru. He believed that rock of every kind—all of what is now classified as igneous, sedimentary, and metamorphic—had precipitated out of solution in a globe-engulfing sea. Granite and serpentine, schist and gneiss had precipitated first and were thus "primitive" rocks, the cores and summits of mountains. "Transitional" rocks (slate, for example) had been deposited underwater on high mountain slopes in tilting beds. As the great sea fell and the mountains dried in the sun, "secondary" rocks (sandstone, coal, basalt, and more) were deposited flat in waters above the piedmont. And while the sea kept withdrawing, "alluvial" rock—the "tertiary," as it was sometimes called—was established on what now are coastal plains. That was the earth's surface as it was formed and had remained. There was no hint of where the water went. Werner was gifted with such rhetorical grace that he could successfully omit such details. He could gesture toward the Saxon hills—toward great pyramids of basalt that held castles in the air—and say, without immediate fear of contradiction, "I hold that no basalt is volcanic." He could dismiss volcanism itself as the surface effect of spontaneous combustion of coal. His ideas may now seem risible in direct proportion to their amazing circulation, but that is characteristic more often than not of the lurching progress of science. Those who laugh loudest laugh next. And some contemporary geologists discern in Werner the lineal antecedence of what has come to be known as black-box geology—people in white coats spending summer days in basements watching million-dollar consoles that flash like northern lights—for Werner's "first sketch of a classification of rocks shows by its meagreness how slender at that time was his practical acquaintance with rocks in the field." The words are Sir Archibald Geikie's, and they appeared in 1905 in a book called *The Founders of Geology*. Geikie, director general of the Geological Survey of Great Britain and Ireland, was an accomplished geologist who seems to have dipped in ink the sharp end of his hammer. In summary, he said of Werner, "Through the loyal devotion of his pupils, he was elevated even in his lifetime into the position of a kind of scientific pope, whose decisions were

final on any subject regarding which he chose to pronounce them. . . . Tracing in the arrangement of the rocks of the earth's crust the history of an original oceanic envelope, finding in the masses of granite, gneiss, and mica-schist the earliest precipitations from that ocean, and recognising the successive alterations in the constitution of the water as witnessed by the series of geological formations, Werner launched upon the world a bold conception which might well fascinate many a listener to whom the laws of chemistry and physics, even as then understood, were but little known." Moreover, Werner's earth was compatible with Genesis and was thus not unpleasing to the Pope himself. When Werner's pupils, as they spread through the world, encountered reasoning that ran contrary to Werner's, pictures that failed to resemble his picture, they described all these heresies as "visionary fabrics" —including James Hutton's *Theory of the Earth; or, an Investigation of the Laws Observable in the Composition, Dissolution, and Restoration of Land Upon the Globe*, which was first presented before the Royal Society of Edinburgh at its March and April meetings in 1785.

Hutton was a medical doctor who gave up medicine when he was twenty-four and became a farmer who at the age of forty-two retired from the farm. Wherever he had been, he had found himself drawn to riverbeds and cutbanks, ditches and borrow pits, coastal outcrops and upland cliffs; and if he saw black shining cherts in the white chalks of Norfolk, fossil clams in the Cheviot Hills, he wondered why they were there. He had become preoccupied with the operations of the earth, and he was beginning to discern a gradual and repetitive process measured out in dynamic cycles. Instead of attempting to imagine how the earth may have appeared at its vague and unobservable beginning, Hutton thought about the earth as it was; and what he did permit his imagination to do was to work its way from the present moment backward and forward through time. By studying rock as it existed, he thought he could see what it had once been and what it might become. He moved to Edinburgh, with its geologically dramatic setting, and lived below Arthur's Seat and the Salisbury Crags, remnants of what had once been molten rock. It was impossible to accept those battlement hills precipitating in a sea. Hutton had a small fortune, and did not have to distract himself for food. He increased his comfort when he invested in a company that made sal ammoniac from collected soot of the city. He performed experiments—in chemistry, mainly. He extracted table salt from a zeolite. But for the most part—over something like fifteen years—he concentrated his daily study on the building of his theory.

Growing barley on his farm in Berwickshire, he had perceived slow destruction watching streams carry soil to the sea. It occurred to him that if streams were to do that through enough time there would be no land on which to farm. So there must be in the world a source of new soil. It would come from above—that was to say, from high terrain—and be made by rain and frost slowly reducing mountains, which in stages would be ground down from boulders to cobbles to pebbles to sand to silt to mud by a ridge-to-ocean system of dendritic streams. Rivers would carry their burden to the sea, but along the way they would set it down, as fertile plains. The Amazon had brought off the Andes half a continent of plains. Rivers, especially in flood, again and again would pick up the load, to give it up ultimately in depths of still water. There, in layers, the mud, silt, sand, and pebbles would pile up until they reached a depth where heat and pressure could cause them to become consolidated, fused, indurated, lithified—rock. The story could hardly end there. If it did, then the surface of the earth would have long since worn smooth and be some sort of global swamp. "Old continents are wearing away," he decided, "and new continents forming in the bottom of the sea." There were fossil marine creatures in high places. They had not got up there in a flood. Something had lifted the rock out of the sea and folded it up as mountains.

One had only to ponder volcanoes and hot springs to sense that there was a great deal of heat within the earth—much exceeding what could ever be produced by an odd seam of spontaneously burning coal—and that not only could high heat soften up rock and change it into other forms of rock, it could apparently move whole regions of the crustal package and bend them and break them and elevate them far above the sea.

Granite also seemed to Hutton to be a product of great heat and in no sense a precipitate that somehow grew in water. Granite was not, in a sequential sense, primitive rock. It appeared to him to have come bursting upward in a hot fluid state to lift the country above it and to squirt itself thick and thin into preexisting formations. No one had so much as imagined this before. Basalt was no precipitate, either. In Hutton's description, it had once been molten, exhibiting "the liquefying power and expansive force of subterranean fire." Hutton's insight was phenomenal but not infallible. He saw marble as having once been lava, when in fact it is limestone cooked under pressure in place.

Item by item, as the picture coalesced, Hutton did not keep it entirely to himself. He routinely spent his evenings in conversation with friends, among them Joseph Black, the chemist, whose responses may have served as a sort of fixed foot to the wide-swinging arcs of Hutton's speculations—about the probable effect on certain materials of varying ratios of temperature and pressure, about the story of the forming of rock. Hutton was an impulsive, highly creative thinker. Black was deliberate and critical. Black had a judgmental look, a lean and sombre look. Hutton had dark eyes that flashed with humor under a far-gone hairline and an oolitic forehead full of stored information. Black is regarded as the discoverer of carbon dioxide. He is one of the great figures in the history of chemistry. Hutton and Black were among the founders of an institution called the Oyster Club, where they whiled away an evening a week with their preferred companions—Adam Smith, David Hume, John Playfair, John Clerk, Robert Adam, Adam Ferguson, and, when they were in town, visitors from near and far such as James Watt and Benjamin Franklin. Franklin called these people "a set of as truly great men . . . as have ever appeared in any Age or Country." The period has since been described as the Scottish Enlightenment, but for the moment it was only described as the Oyster Club. Hutton, who drank nothing, was a veritable cup running over with enthusiasm for the achievements of his friends. When Watt came to town to report distinct progress with his steam engine, Hutton reacted with so much pleasure that one might have thought he was building the thing himself. While the others busied themselves with their economics, their architecture, art, mathematics, and physics, their naval tactics and ranging philosophies, Hutton shared with them the developing fragments of his picture of the earth, which, in years to come, would gradually remove the human world from a specious position in time in much the way that Copernicus had removed us from a specious position in the universe.

A century after Hutton, a historian would note that "the direct antagonism between science and theology which appeared in Catholicism at the time of the discoveries of Copernicus and Galileo was not seriously felt in Protestantism till geologists began to impugn the Mosaic account of the creation." The date of the effective beginning of the antagonism was the seventh of March, 1785, when Hutton's theory was addressed to the Royal Society in a reading that in all likelihood began with these words: "The purpose of this Dissertation is to form some estimate with regard to the time the globe of this Earth has existed." The presentation was more or less off the cuff, and ten years would pass before the theory would appear (at great length) in book form. Meanwhile, the Society required that Hutton get together a synopsis of what was read on March 7th and finished on April 4, 1785. The present quotations are from that abstract.

We find reason to conclude, *1st*, That the land on which we rest is not simple and original, but that it is a composition, and had been formed by the operation of second causes. *2dly*, That before the present land was made there had subsisted a world composed of sea and land, in which were tides and currents, with such operations at the bottom of the sea as now take place. And, *Lastly*, That while the present land was forming at the bottom of the ocean, the former land maintained plants and animals . . . in a similar manner as it is at present. Hence we are led to conclude that the greater part of our land, if not the whole, had been produced by operations natural to this globe; but that in order to make this land a permanent body resisting the operations of the waters two things had been required; *1st*, The consolidation of masses formed by collections of loose or incoherent materials; *2dly*, The elevation of those consolidated masses from the bottom of the sea, the place where they were collected, to the stations in which they now remain above the level of the ocean. . . .

Having found strata consolidated with every species of substance, it is concluded that strata in general have not been consolidated by means of aqueous solution. . . .

It is supposed that the same power of extreme heat by which every different mineral substance had been brought into a melted state might be capable of producing an expansive force sufficient for elevating the land from the bottom of the ocean to the place it now occupies above the surface of the sea. . . .

A theory is thus formed with regard to a mineral system. In this system, hard and solid bodies are to be formed from soft bodies, from loose or incoherent materials, collected together at the bottom of the sea; and the bottom of the ocean is to be made to change its place . . . to be formed into land. . . .

Having thus ascertained a regular system in which the present land of the globe had been first formed at the bottom of the ocean and then raised above the surface of the sea, a question naturally occurs with regard to time; what had been the space of time necessary for accomplishing this great work? . . .

We shall be warranted in drawing the following conclusions; *1st*, That it had required an indefinite space of time to have produced the land which now appears; *2dly*, That an equal space had been employed upon the construction of that former land from whence the materials of the present came; *Lastly*, That there is presently laying at the bottom of the ocean the foundation of future land. . . .

As things appear from the perspective of the twentieth century, James Hutton in those readings became the founder of modern geology. As things appeared to Hutton at the time, he had constructed a theory that to him made eminent sense, he had put himself on the line by agreeing to confide it to the world at large, he had provoked not a few hornets

into flight, and now—like the experimental physicists who would one day go off to check on Einstein by photographing the edges of solar eclipses—he had best do some additional travelling to see if he was right. As he would express all this in a chapter heading when he ultimately wrote his book, he needed to see his "Theory confirmed from Observations made on purpose to elucidate the Subject." He went to Galloway. He went to Banffshire. He went to Saltcoats, Skelmorlie, Rumbling Bridge. He went to the Isle of Arran, the Isle of Man, Inchkeith Island in the Firth of Forth. His friend John Clerk sometimes went with him and made line drawings and watercolors of scenes that arrested Hutton's attention. In 1968, a John Clerk with a name too old for Roman numerals found a leather portfolio at his Midlothian estate containing seventy of those drawings, among them some cross-sections of mountains with granite cores. Since it was Hutton's idea that granite was not a "primary" rock but something that had come up into Scotland from below, molten, to intrude itself into the existing schist, there ought to be pieces of schist embedded here and there in the granite. There were. "We may now conclude," Hutton wrote later, "that without seeing granite actually in a fluid state we have every demonstration possible of this fact; that is to say, of granite having been forced to flow in a state of fusion among the strata broken by a subterraneous force, and distorted in every manner and degree."

What called most for demonstration was Hutton's essentially novel and all but incomprehensible sense of time. In 4004 + 1785 years, you would scarcely find the time to make a Ben Nevis, let alone a Gibraltar or the domes of Wales. Hutton had seen Hadrian's Wall running across moor and fen after sixteen hundred winters in Northumberland. Not a great deal had happened to it. The geologic process was evidently slow. To accommodate his theory, all that was required was time, adequate time, time in quantities no mind had yet conceived; and what Hutton needed now was a statement in rock, a graphic example, a breath-stopping view of deep time. There was a formation of "schistus" running through southern Scotland in general propinquity to another formation called Old Red Sandstone. The schistus had obviously been pushed around, and the sandstone was essentially flat. If one could see, somewhere, the two formations touching each other with strata awry, one could not help but see that below the disassembling world lie the ruins of a disassembled world below which lie the ruins of still another world. Having figured out inductively what would one day be called an angular unconformity, Hutton went out to look for one. In a damp country covered with heather, with gorse and bracken, with larches

and pines, textbook examples of exposed rock were extremely hard to find. As Hutton would write later, in the prototypical lament of the field geologist, "To a naturalist nothing is indifferent; the humble moss that creeps upon the stone is equally interesting as the lofty pine which so beautifully adorns the valley or the mountain: but to a naturalist who is reading in the face of rocks the annals of a former world, the mossy covering which obstructs his view, and renders undistinguishable the different species of stone, is no less than a serious subject of regret." Hutton's perseverance, though, was more than equal to the irksome vegetation. Near Jedburgh, in the border country, he found his first very good example of an angular unconformity. He was roaming about the region on a visit to a friend when he came upon a stream cutbank where high water had laid bare the flat-lying sandstone and, below it, beds of schistus that were standing straight on end. His friend John Clerk later went out and sketched for Hutton this clear conjunction of three worlds—the oldest at the bottom, its remains tilted upward, the intermediate one a flat collection of indurated sand, and the youngest a landscape full of fences and trees with a phaeton-and-two on a road above the rivercut, driver whipping the steeds, rushing through a moment in the there and then. "I was soon satisfied with regard to this phenomenon," Hutton wrote later, "and rejoiced at my good fortune in stumbling upon an object so interesting to the natural history of the earth, and which I had been long looking for in vain."

What was of interest to the natural history of the earth was that, for all the time they represented, these two unconforming formations, these two levels of history, were neighboring steps on a ladder of uncountable rungs. Alive in a world that thought of itself as six thousand years old, a society which had placed in that number the outer limits of its grasp of time, Hutton had no way of knowing that there were seventy million years just in the line that separated the two kinds of rock, and many millions more in the story of each formation—but he sensed something like it, sensed the awesome truth, and as he stood there staring at the riverbank he was seeing it for all mankind.

To confirm what he had observed and to involve further witnesses, he got into a boat the following spring and went along the coast of Berwickshire with John Playfair and young James Hall, of Dunglass. Hutton had surmised from the regional geology that they would come to a place among the terminal cliffs of the Lammermuir Hills where the same formations would touch. They touched, as it turned out, in a headland called Siccar Point, where the strata of the lower formation had been upturned to become vertical columns, on which rested the Old Red Sand-

stone, like the top of a weather-beaten table. Hutton, when he eventually described the scene, was both gratified and succinct—"a beautiful picture . . . washed bare by the sea." Playfair was lyrical:

On us who saw these phenomena for the first time, the impression made will not easily be forgotten. The palpable evidence presented to us, of one of the most extraordinary and important facts in the natural history of the earth, gave a reality and substance to those theoretical speculations, which, however probable, had never till now been directly authenticated by the testimony of the senses. We often said to ourselves, What clearer evidence could we have had of the different formation of these rocks, and of the long interval which separated their formation, had we actually seen them emerging from the bosom of the deep? We felt ourselves necessarily carried back to the time when the schistus on which we stood was yet at the bottom of the sea, and when the sandstone before us was only beginning to be deposited, in the shape of sand or mud, from the waters of a superincumbent ocean. An epocha still more remote presented itself, when even the most ancient of these rocks, instead of standing upright in vertical beds, lay in horizontal planes at the bottom of the sea, and was not yet disturbed by that immeasurable force which has burst asunder the solid pavement of the globe. Revolutions still more remote appeared in the distance of this extraordinary perspective. The mind seemed to grow giddy by looking so far into the abyss of time.

Hutton had told the Royal Society that it was his purpose to "form some estimate with regard to the time the globe of this Earth has existed." But after Jedburgh and Siccar Point what estimate could there be? "The world which we inhabit is composed of the materials not of the earth which was the immediate predecessor of the present but of the earth which . . . had preceded the land that was above the surface of the sea while our present land was yet beneath the water of the ocean," he wrote. "Here are three distinct successive periods of existence, and each of these is, in our measurement of time, a thing of indefinite duration. . . . The result, therefore, of this physical inquiry is, that we find no vestige of a beginning, no prospect of an end."

The Old Red Sandstone was put down by rivers flowing southward to a sea where marine strata were accumulating in the region that is now called Devon. The size, speed, and direction of the rivers—their islands, pitches, and bends—are not just inferable but can almost be seen, in structures in the Old Red Sandstone: gravel bars, point bars, ripples of the riverbeds, migrating channels, "waves" that formed of sand. The sea into which those rivers spilled ran all the way to Russia, but it was in the rock of Devonshire that geologists in the eighteen-thirties found cup corals—fossilized skeletons, cornucopian in shape—that were not of an age with corals they had found before. They had found related corals that were obviously less developed than these, and they had found corals that were more so.