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Chapter 9

Subterranean Fires

James Hutton

Histories of geology generally present Werner first and then his Scottish adversary Hutton (1726–1797), although Hutton was born twenty-four years before Werner. The reason lies in the 1795 publication date of the final two-volume edition of Hutton's *Theory of the Earth*,[1] and in the ensuing controversy, which was essentially upheld by his disciple John Playfair (1748–1819).[2] Therefore, the Wernerian system was published a few years before Hutton's.

Hutton was a man of the Enlightenment. He had studied medicine in the first half of the century and defended his thesis the year Werner was born. This thesis partly explains his theory of the earth because it describes blood circulation in the microcosm, that is, in humans (in Latin, *De sanguine et circulatione microcosmi*).[3] Hutton's geological theory was based, in turn, on circulation of matter. He became interested in geology only after he had abandoned medicine and devoted himself to agriculture. Soil is a product of weathering rocks, and soil is necessary for plants to grow. Therefore, mountains have to be eroded to form arable land. However, soil is transported by running water toward the sea; this movement from top to bottom would level continents if it were not compensated for by a movement in the opposite direction that repairs the effects of erosion. The author was so close to the biological model of circulation that he compared the earth to an "organized body."[4]

So the old metaphor of the microcosm was back. Looking at these rather naive proposals of a physician-farmer who deduced uplifting of mountains from the necessity of maintaining land for the perpetuation of the human race, we might ask if no other proposition could have been used to refute geognosy and its observations, which were so useful to miners.

Let us not judge too quickly, for Hutton was also interested in technical progress. What perhaps anticipated his model of geological processes of the earth was his excellent understanding of the steam engine. He was a friend of James Watt, inventor of this engine, and Hutton's geological cycles certainly resulted as much from his interest in the steam engine as from blood circulation in the human microcosm.

Subterranean Heat

Hutton's system was based on the action of subterranean fire or heat, to which he attributed three effects: induration of sediments, uplifting of strata and formation of mountains, and granitic intrusion in liquid form into layers.

Earlier we called the theory of the igneous origin of granite plutonism and contrasted it to the neptunist theory of the supposed aqueous origin of igneous and metamorphic rocks. It was, however, not the problem of the origin of granite that started the controversy between plutonists and neptunists. Frank Dawson Adams put it this way: "The question as to how it came about that the incoherent sediments laid down in the sea became compacted into solid rocks, was one which presented itself to every observer, but to which the Neptunists and Plutonists gave entirely different answers."[5]

Everyone wondered about the process, today known as **diagenesis,** that changed unconsolidated deposits at the bottom of the ocean or a lake into solid rocks. The simplest answer was to assume a cementation by dissolved substances, which filled the interstitial spaces between superposed particles. This was the belief of neptunists, and it is indeed the process of transforming sand into sandstone. Hutton said, however, that induration occurs sometimes with substances already known to be insoluble (silica in sandstone, for example). He reasoned that a substance therefore becomes liquid by a process different from dissolution, namely, melting by heat. He maintained that fire melts a portion of the sediment by fusing together particles that have remained solid; upon cooling, this portion becomes solid.

From this perspective, the Huttonian thesis naturally seems inadequate. His adversaries were closer to understanding the actual processes of diagenesis. However, at that time, no one could decide between the two answers; to opt for just one explanation seemed unnecessarily extreme. This is why the qualifying (and pejorative) adjectives of plutonist and neptunist are used to indicate the followers of the two opposed doctrines.

However, his thesis led Hutton to two other propositions, mentioned above, which are truly innovative and have remained so to the present day. The problems of the uplifting of earth layers and of the origin of granite shall be investigated separately.

Angular Unconformities

We owe to Hutton the discovery of what is known today as angular unconformity, by means of which geologists still recognize and date orogenic movements. Let us imagine that a series of horizontal rock layers is compressed and folded. The deformed layers are immediately attacked by erosion, which levels them gradually. The folds are thus truncated by the topographic surface, as if they had been cut off. If the area is subsequently covered by the sea, the newly deposited sediments rest "unconformably" on their substratum; that is, the new layers form an angle with the ancient folded and truncated layers. In extreme cases, folded layers are vertical and layers before and after the tectonic movement are at a right angle (fig. 9.1).

Angular unconformities allow us to date uplifting if the age of the rock layers is known. The movement is considered to have occurred after the youngest folded layer and before the oldest horizontal layer.

To follow Hutton's discovery of angular unconformities, one must read his *Theory of the Earth*. Fortunately, the chapters were written without being revised so that the stages of the evolution of his thinking can be found. In 1785 Hutton first read a dissertation at the Royal Society of Edinburgh: *Concerning the System of the Earth, Its Duration and Stability.*[6] An abstract was published soon after, and the complete text appeared in a journal in 1788, entitled: "Theory of the Earth; or an Investigation of the Laws Observable in the Composition, Dissolution, and Restoration of Land upon the Globe."[7] Finally, in 1795, the Scottish physician published the complete version of

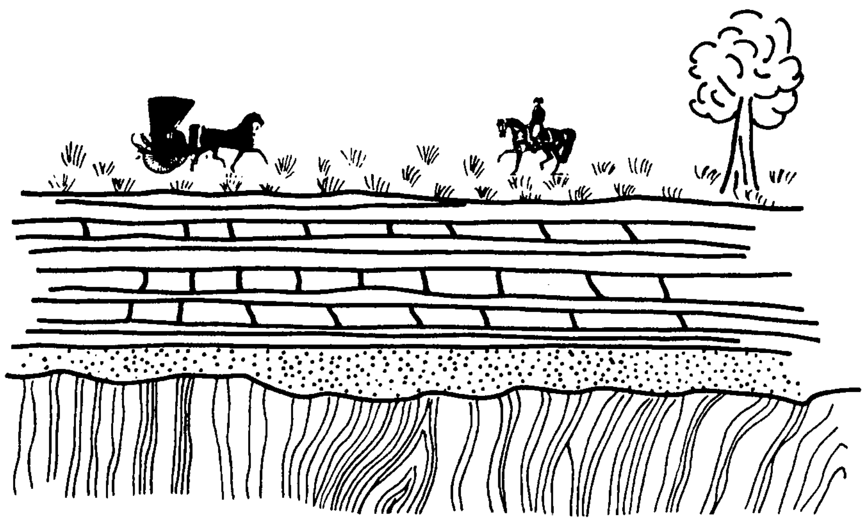

Figure 9.1. Hutton's Diagram of an Angular Unconformity (From Theory of the Earth*, 1795). The lower vertical layers are the "roots" of ancient folds, which were partly destroyed by erosion. The peneplained surface was covered by the sea, which deposited the upper horizontal layers.*

Theory of the Earth, with Proofs and Illustrations, in which the dissertation forms the first chapter.[8]

However, Hutton's first chapter and the three following ones in the first edition do not mention any unconformity. This shows that he added the idea later on. According to one of his biographers, Hutton supposedly wrote the main parts of his theory as early as 1760, and he understood the igneous origin of basalt before Desmarest.[9] However, so long as he lacked the concept of angular unconformity, the work remained unfinished.

Predictive Theory

In chapter 5 of *Theory of the Earth,* the author wondered about portions of the earth that had been several times covered by water and then exposed to the air. He mentioned that some naturalists, such as J.-A. Deluc, had seen horizontal limestones resting upon folded schists—without, however, recognizing the significance of the situation. Hutton understood that these schists had been cut off by erosion, that is, exposed to weathering agents, before limestones were

deposited on top. He *predicted,* therefore, the existence of angular unconformities.

In chapter 6, he stated his first observations on that subject. He at first saw layers inclined at an angle of 45° in opposite directions, thus representing the two legs of the Greek letter lambda. Then he observed horizontal layers resting upon vertical ones (see fig. 9.1).

This latter arrangement presented a problem if one followed Hutton's concept, because he stated that uplifting of layers also caused their tilting. If layers remained horizontal, they must consequently have been uplifted without any disturbance. But who can prove that they were uplifted? J.-A. Deluc, who had seen angular unconformities before Hutton, stated that if horizontal limestones had been uplifted, as had the schists on which they rest, they would have been "broken and disturbed in the same fashion."[10] This was common sense.

Fortunately, Hutton was not influenced by such commonsense arguments. After having predicted the observation in chapter 5, he went looking for these "junctions" or "contacts," which he then described in chapter 6 as observations on the island of Arran, at Jedburgh and Siccar Point.

What remained to be done was to date these superposed layers. Like his contemporaries, Hutton talked about primary and secondary layers. However, their age was determined by the angular unconformity, so that the folded strata were primary and the others secondary. Today, we know that it is not possible to date the angular unconformity itself, although it can give the relative age of the layers of rock formations. Thus, angular unconformity acts as an archive because it has the double function of revealing and dating orogenic events. Angular unconformities thus replaced, in a certain way, the lithological archives of Werner (and other neptunists), who associated age with the nature of layers.

Hutton believed that angular unconformities have the same age wherever they occur. Like neptunists, who believed that granite or gneiss were of the same age everywhere, plutonists had to accept the idea that the upheaval that had created continents was an event that had occurred at the same time over the entire globe. The history of mountain building could not be done on a regional basis.

Because Hutton was searching for a model of earth processes, he established a cyclic theory, where the same phenomena recur indefinitely. The concept led him to write the famous phrase, which seemed to reject the Creation and led to accusations of impiety: "We find no vestige of a beginning, no prospect of an end."[11] However, cyclicity destroys most traces of former cycles. We notice here again that cyclic theories are not suitable for historical purposes. In particular, as was the case for Hutton, cyclic theories based on the existence of deep erosion and melting by heat of materials depend on processes that tend to erase archives.

In fact, in his explanation of how land actually became habitable, he wrote that not two, but three successive worlds had to follow each other:

> If the earth on which we live began to appear in the ocean at the time when the last began to be resolved, it could not be from the materials of the continent immediately preceding this which we examine, that the present earth had been constructed; for the bottom of the ocean must have been filled with materials before land could be made to appear above its surface. . . . 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, in ascending from the present, we consider as the third, and 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.[12]

The Igneous Origin of Granite

The theory of the igneous origin of granite is the third aspect of Hutton's plutonistic theory. It is perhaps the most daring element considering that penetrating minds such as Werner, Dolomieu, and Saussure still believed in the aqueous origin of granite as the first deposit at the bottom of the universal ocean. Again, the *Dissertation* of 1785 mentioned nothing; but in the summer of the same year, Hutton visited Glen Tilt where he observed that granite—obviously in a liquid state—had intruded rocks. He repeated his observations the following summers. In 1787, on the island of Arran, he also discovered angular unconformities.[13]

Hutton was accompanied by two students. One was John Playfair, who, as mentioned above, popularized the Huttonian theory in his 1802 *Illustrations of the Huttonian Theory of the Earth.*[14] The other was James Hall (1761–1832), known for his essays in experimental geology, one of which referred specifically to the question of intrusive granite.

Granitic intrusions drive back rock layers, which undergo important lateral stresses. Hall tried to show this in a model. He piled sheets of cloth horizontally, one above the other. He placed vertical boards on both sides and then pushed them slowly together so as to simulate lateral forces. Weights placed on top of the pile of cloth represented the overlying sedimentary cover. Thus, Hall obtained folded sheets corresponding to the large undulations he had observed in the field with Hutton and Playfair.[15]

Together with his two students, Hutton succeeded in presenting an explanation of all the orogenic phenomena: rising molten granite compresses, folds, and uplifts layers deposited at the bottom of the sea and makes them emerge as mountain chains, which later undergo the effects of erosion. But his theory and the observations on which it was based—angular unconformities on the one hand, and granitic intrusions on the other—were known by his contemporaries only through a short article published in 1794.[16] The other new findings were meant to form volume 3 of the *Theory of the Earth.* However, they remained in manuscript for a century, until 1899, when Archibald Geikie edited and published volume 3.[17]

There is no doubt that these new ideas surprised neptunists, who were busy classifying the layers of the earth but were little interested in such an ahistorical approach. However, among the neptunists were geologists who had also observed lateral compressions of layers and made an attempt to explain them.

Saussure and Dolomieu

In his exploration of the Alps, Saussure had seen "layers forming a 'C' or an 'S'"; that is, recumbent folds with a nearly horizontal axis. He explained these folds as "a refoulement [horizontal **thrust**] which has folded" the left and right parts of a layer "one above the other," much like a pancake folded in two. What he believed to be the clue was the presence of an "empty space" at the site where the folded part had been before the movement.[18] Strangely enough, he stopped there, at least in his *Voyage dans les Alpes*. He had broken the Wernerian heritage, but seemed incapable of proceeding any further. Carozzi's study of his manuscripts shows, however, that Saussure actually had considered large-scale—even global—horizontal thrusting, and that he realized that this meant large-scale shortening of the crust and the underlying sliding planes. These ideas came close to the concept of contraction of the crust due to the cooling of the earth (chapter 12).[19]

Déodat de Dolomieu had also observed large-scale folding in mountains. He said that the structure of the Alps brings to mind "a shock that, hitting obliquely against the consolidated crust of our Earth, compressed this crust, broke it with violence, displaced and uplifted layers, and forced some of them to prop up or to support each other in a standing position, as is the case of Mont Blanc, while others fell after the shock and were thrusted over underlying masses . . . such as the rocks which form Monte Rosa."[20]

However, the larger the scale of the phenomenon, the less reasonable the solution. For instance, Dolomieu said that he had "a weak spot" for Whiston's system, meaning the explanation given in 1696 by William Whiston, disciple of Newton, in *A New Theory of the Earth* for the formation of mountains by the action of a comet.[21] An "extraterrestrial shock," said Dolomieu, that broke "the shell of the Earth" might well have produced the described effects.[22]

Saussure and Dolomieu lagged behind Hutton in their search for an explanation of compression (the effects of which they observed with as much precision as Hutton); whereas Henri Gautier (1660–1731), a civil engineering inspector in the Languedoc, France, had expressed quite early some revolutionary ideas with respect to tectonics.

Gautier

Gautier's contemporaries knew his ideas well—Bourguet refuted him at length, though without naming him, and Maillet devoted twenty pages in his *Telliamed* to the same purpose—but he was completely forgotten later on. It took François Ellenberger's recent works to restore this author to the position he deserved.[23]

Gautier was aware of deformation of rock layers in mountains. In 1721 he wrote in his *Nouvelles Conjectures sur le Globe de la Terre* that, if sedimentary layers are comparable to "a recently constructed building," rock layers in mountains are similar to "another building which was knocked down, in which brick layers are overturned, appear upside down, thrown sidewise or some other way."[24]

Like Dolomieu and Saussure, Gautier accepted lateral movements to explain this deformation. The segments of the earth's crust "become superposed and form mountains . . . much like ice rafts floating on a river, which, when they encounter obstacles, override each other and form mountains of ice."[25]

But if we want to count Gautier as a forerunner of Hutton we must stop right there because in other respects he was very much an author of his own time. Indeed, he was even pre-Newtonian in his use of Cartesian physics, and he proposed a very strange representation of the structure of the planet, which probably led his readers astray. He believed that the earth was hollow, or rather filled with an "air much more subtile" than the atmosphere, so that the earth resembled a barrel "emptied of its wine." The crust of this globe was very thin, only 5,390 toises (about 10 kilometers). Even more bizarre was Gautier's belief that the interior and exterior surfaces of the crust were symmetrical; that is, seas and mountains existed inside the planet as well as on its surface (Gautier illustrated this idea with a sketch). He said that the reasons for this symmetric structure lay in two opposing forces: gravity and a "central force" caused by the rotation of the earth. The two forces canceled each other out in the middle of the crust. Thus, the central force dominated underneath and produced the same effects as gravity, but in the opposite direction.

The Huttonian theory is, of course, much closer to modern theories than Gautier's. For instance, Hutton's idea of a subterranean fire, going back to Descartes' central fire, is still popular today. Erupting volcanoes, even to people who have only seen them on television or film, suggest that the interior of the earth consists of molten matter, even if there is no proof that this "fire" reaches all the way to the center of the earth.

Needham and the Steam Engine

Like Hutton, Dolomieu believed that below the earth's crust existed a subterranean fire that ejected basaltic lavas.[26] In 1769, before Hutton and Dolomieu, John Turberville Needham had proposed the same theory in the course of experiments he did with Buffon to prove spontaneous generation of living creatures. The concept of spontaneous generation had been seriously contested by Lazzaro Spallanzani. To a French translation of Spallanzani's essay, *Nouvelles Recherches sur les découvertes microscopiques* (New research on microscopic discoveries), Needham added a lengthy work, which translates in English to *Physical and Metaphysical Essay on the Nature of Religion, with a New Theory of the Earth, and Measurements of the Elevation of the Alps*).[27] Needham explained, in particular, that "a central fire which reached up to the surface of the Earth" produced the "internal expansive forces" that lift the earth's crust and produce plains when the terrestrial masses resist these forces, mountains (hollow inside) when they resist partially and become uplifted, or volcanoes when they (terrestrial masses) break.[28]

Needham's most original idea on mountain building was the analogy he saw with a "machine" using force "either produced by steam, or by extremely thin and dry air."[29] This model is interesting because it comes close to the image of the steam engine. Unlike Hutton, Needham could not have gotten the idea directly from Watt, because Watt only made his first (failed) experiments in 1769, the year Needham's book appeared. Nevertheless, the idea was very much in the air: as early as 1705, Thomas Newcomen had built a machine using the force of steam.

The invention of the steam engine was important not just because it domesticated fire and made it useful for humans, but also because it provided a model for the uplifting of mountains. Until that time, naturalists described the action of fire by comparing it to cannon powder; that is, an explosion that ejects matter by pulverizing it. This image described perhaps the chaos among volcanic debris but did not explain a slow uplifting of mountains. The steam engine thus presented a stimulus for further research by providing a new and better model to explain mountain building.

But how was this internal fire maintained? To run a steam engine, a source of heat is needed. Earlier, Descartes had described the earth as a cold star that retained in its center the matter of the first element. Leibniz and Buffon had adopted this theory, saying, however, that their star had cooled down to the core. J. J. Dortous de Mairan had searched for proof of a permanent internal heat source in the earth's core, at first in 1719, and then in 1765 (thus at the same time as Needham). However, he did not draw any conclusions in regard to mountain building.[30] Moro, who did assert the uplifting of lands, had sketched a world with a central fire, but only in a hypothetical fashion; he explained that uplifting did not create an empty space because a fluid earth fills in the space caused by the deformation of the crust.

Hutton, pressed by his adversaries, had to find a solution. The solution he came up with was a simple one and not at all new: combustion of coal. Most eighteenth-century naturalists had given this interpretation for the origin of volcanic fires. Nevertheless, Hutton made it a permanent cause, saying that each cycle forms new continents, which produce new forests; their destruction in turn forms new layers of coal.

Werner and Hutton

To conclude this chapter, the merits of Werner and Hutton and their respective roles in the establishment of geological science are contrasted and compared. One should remember that Hutton's "plutonistic" explanation of diagenesis of rocks (namely, induration) was erroneous. But he understood the origin of granite better than Werner did. His student, James Hall, succeeded in crystallizing calcium carbonate powder into limestone. In a sealed metal tube, calcium carbonate was heated under pressure to the melting point of silver in 1805.[31] These were the first laboratory tests in experimental metamorphism. Yet it took another century and a half to produce granite by fusion (experimental anatexis, that is, the process by which igneous rocks remelt into magma). Experiments by J. Wyart and G. Sabatier in France and by H.G.F. Winkler in Germany in the 1960s demonstrated that sediments, at a pressure of 2,000 bars and a temperature of 800° C, become a liquid with the composition of granite. The formation of granite is therefore a phenomenon that has always existed and which occurs at great depth. It is not an ancient and unique event that occurred only in the "primitive" epoch of the history of the earth.

Thanks to James Hall's laboratory demonstration, the igneous origin of granite was accepted rather quickly, and geology became Huttonian. Geology kept nothing from the Wernerian neptunism except the historical preoccupation that Hutton's theory lacked. But without that sense of geological history, Hutton's cyclicity would not have been of any use.

Hutton triumphed also in matters of tectonics. Werner was not interested in deformation of strata. His system forbade it by its claim that rock layers had kept their order of deposition. Hutton, on the other hand, proposed a key for the recognition of uplifting. In that respect, he complemented Steno's tectonic principle of deformation of beds after deposition (see chapter 5) and provided, 130 years after Steno, the second milestone of modern geology. The methodology of both Hutton and Steno became an integral part of science and allowed the geognostic chronology to be completely redone and a new, definitive understanding of earth's history to be established.

Because Hutton was not interested in the history of the earth, he was to neptunists what Newton was to Cartesians: he abandoned history for the benefits of an operational law. However, with that law, he provided the key that allowed his successors to read history.

Repeated Uplifts

At the same time, Hutton proposed the idea the neptunists lacked: that the history of the earth is based on repeated phases of uplifting of mountains. This idea was not new; the cycles of the Stoics represented the first version of this concept. However, the Stoics were long forgotten.

Hutton's era may be considered a kind of return to the ideas of the Stoics. Indeed, in the middle of the eighteenth century, Nicolas-Antoine Boulanger visualized a cyclic system with periodical restorations of the earth (it was just as unhistorical as Hutton's because each cycle erased the traces of former cycles). Gautier, before Boulanger, also proposed a geology punctuated by orogenic cycles. Finally, two famous contemporaries of Hutton, each in his own way, presented ideas of cyclicity.

The first was Jean Baptiste Lamarck (1744–1829), who is best known for his ideas on evolution. But he also tackled geology. In his book *Hydrogeology*, published in 1802, he argued that the axis of the poles changes imperceptibly together with the "equatorial bulge"—the swelling of the earth around the equator.[32] That swelling is greater for continents than for the ocean. Therefore, the highest lands are at the equator because the ellipsoidal shape of the earth protrudes more than the ocean does. Hence, land dominates over the ocean at the equator. Because the axis of the poles rotates about the earth in 9 million centuries, the lands and the seas undergo a cycle that brings to mind Buridan's long cycle (chapter 2). Boulanger also mentioned changes of the axis of the poles and of the shape of the terrestrial spheroid, but he claimed these changes were more violent in character.

The second author was Jean-André Deluc, a geologist from Geneva who lived in England for a long time and was one of Hutton's adversaries. He believed that mountain building required "revolution upon revolution." However, these catastrophes were not uplifts but collapses caused by internal cavities according to the old ideas of Leibniz and Buffon. Deluc was appalled by the disorder of layers, which looked like "masures" or "buildings in a state of ruins."[33] Whatever angular unconformities he might have seen persuaded him that rock formations were not uplifted.

Nevertheless, it would be unfair to laugh at Deluc's archaic tectonics or his concerns as a scrupulous Christian about reconciling

Scriptures and geological observation, worked out in particular in his 1798 *Lettres sur l'histoire physique de la terre, adressées à M. le professeur Blumenbach, renfermant de nouvelles preuves géologiques et historiques de la mission divine de Moyse* (Letters on the physical history of the earth, sent to Professor Blumenbach, including new geological and historical proofs of the Divine mission of Moses). Indeed, when he explained that *present* mountains were caused by repeated orogenies, he introduced the notion of tectonic phases into the history of the earth. He thought that mountains were not destroyed from one stage to the other; on the contrary, they became progressively higher by the cumulative results of "revolutions." If he did not understand the importance of angular unconformities, at least he noticed the repetitive character of mountain building. More important, he was one of the first to understand the use of fossils in stratigraphy, as we shall see in the next chapter.