MARTIN RUDWICK

16 Minerals, strata and fossils

Animal, vegetable or mineral? The opening move of the traditional guessing game preserves part of what was the taken-for-granted structure of the sciences, at least until the end of the eighteenth century. 'Natural history' was at that time still a highly esteemed branch of human knowledge, and no merely amateurish pursuit. It was not an archaic synonym for what would now be called biology, for it ignored the boundary between the living and the non-living: it included mineralogy as one of three divisions or 'kingdoms' of equal importance (the others were, of course, zoology and botany). But 'mineralogy' was much wider in meaning than the modern science of the same name; it was roughly the equivalent of 'earth sciences' today. The term 'geology' had indeed been proposed, but it was a neologism that was neglected or even rejected, for reasons that will become clear later in this chapter. In fact the shift from 'mineralogy' to 'geology', as the most usual term for what would now be called the earth sciences, encapsulates the dramatic changes in the culture of inorganic natural history that occurred between the late-eighteenth and the mid-nineteenth centuries.

A science of specimens

In the late eighteenth century, throughout Europe and wherever European culture extended, mineralogy was first and foremost a matter of mineral specimens: specimens collected, sorted, named and classified. Specimens were extracted from mines and quarries, hammered out of coastal cliffs or mountain crags, picked out of stream-beds or off the surface of fields, and assembled indoors in museums or private 'cabinets'. Those who collected these specimens called themselves 'mineralogists' or, more broadly, just 'naturalists'. Some, for example the owners or managers of mines, made their collections for strictly practical reasons; but most did so as a socially acceptable part of polite culture, valuing above all the unusual and the spectacular, with motives that might be at the same time aesthetic, scientific and monetary. Rare or valued specimens were exchanged between enthusiasts, purchased when a

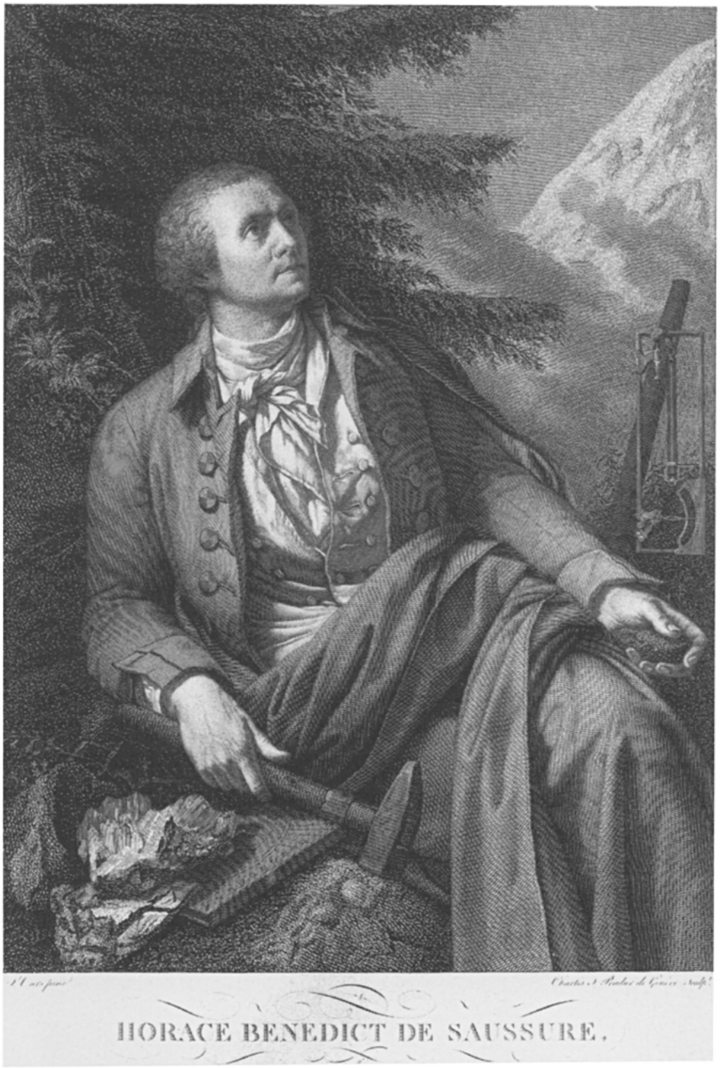


Figure 16.1 A highly emblematic portrait of Horace Bénédict de Saussure (1740–99), one of the most distinguished of the late eighteenth-century naturalists who studied the mineral kingdom. He is dressed to match his social status in the polite society of Geneva, but he is portrayed outdoors as if doing fieldwork. He has in his hands a miner's hammer – the badge of the mineralogist – and a rock specimen obtained by its use; by his side are mineral specimens and the bag in which he has collected them, and instruments for surveying the topography and measuring the inclination of rock strata; and he looks up – in a gaze recalling the pious poses of saints in an earlier iconography – towards the Alpine peaks in the background. By 1796, when Saint-Ours painted the portrait on which this engraving is based, the fifty-six-year-old Saussure had in fact suffered a paralysing stroke and his fieldwork career was over. From a print in the author's collection.

deceased or bankrupt naturalist's collection was put up for sale, and – not least – bought from the miners, quarrymen and peasants whose daily toil enabled them to find what these noblemen and gentlemen (and a few ladies) were prepared to pay for.

At least in the more serious collections, specimens were then compared with those of other naturalists, identified and named. As standards of comparison, collections of specimens that had been named authoritatively were particularly valued, and were exchanged between individuals or institutions. Comparisons were often made, however, not with other real specimens, but with what were in effect the *proxy* specimens pictured in publications (Figure 16.2). These were usually engravings, which were sometimes

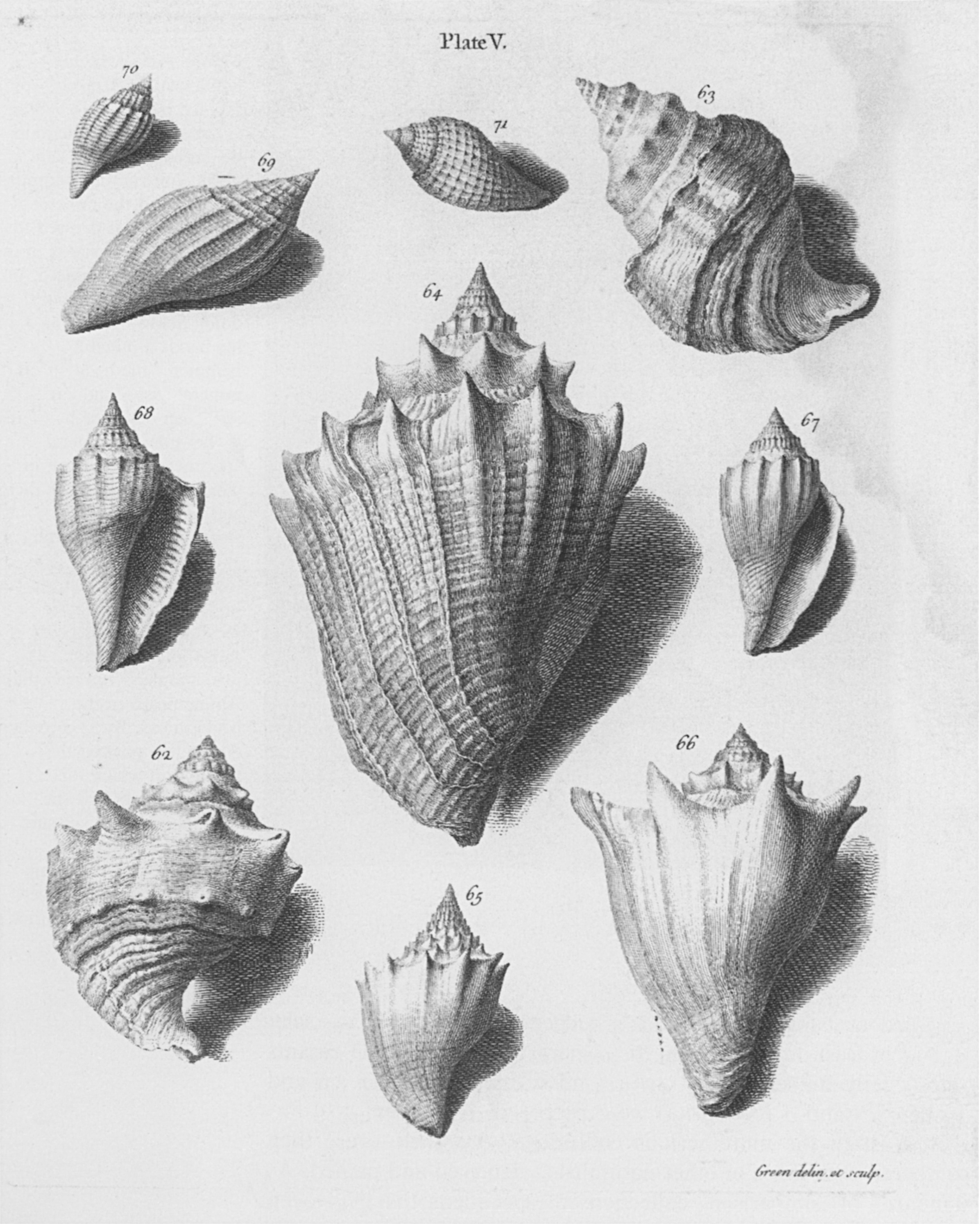


Figure 16.2 A typical set of eighteenth-century illustrations of fossils: these are of well-preserved mollusc shells from Secondary (in modern terms, Cenozoic) strata in the south of England. Such engraved representations – minerals were depicted in a similar style – formed highly effective proxies for the real specimens. From Gustav Brander's *Fossilia Hantoniensia collecta* (London, 1766), illustrating specimens preserved in the British Museum in London.

hand-coloured with astonishing *trompe l'oeil* realism. Books with illustrations of mineral specimens, often recording a celebrated collection or material from some famous locality, were in effect proxy museums, and they spread their authors' descriptions and identifications as widely as the volumes were bought and sold.[1]

In all this, mineralogy differed little from the other branches of natural history. As in botany and zoology, the fundamental scientific goal was simply to describe, name and classify the diverse riches of nature. Minerals, no less than plants and animals, were to be described in terms of their natural *species*: species such as quartz and felspar, no less than species of daisies and deer. But most mineralogists, like other naturalists, were not content merely to identify and name their specimens. They wanted to construct a classification that would assemble similar minerals into a nesting set of groups, and so reveal the hierarchical structure of the diversity of the whole mineral kingdom.

In this task of identification and classification, it was increasingly regarded as imperative to examine the interior of minerals, as it were, as much as that of plants and animals. While the botanist dissected the intimate sexual parts of the flower, and the zoologist the literally internal anatomy of the animal body, the mineralogist resorted to the laboratory, and performed chemical analysis on his specimens in order to discover their true nature. In this way mineralogy had developed some of its strongest links with chemistry. The emergence of what became known as crystallography, at the end of the eighteenth century, provided a further set of characters for the same task of constructing a truly natural classification of minerals; but it also brought to mineralogy the prestige of being geometrical and quantitative.

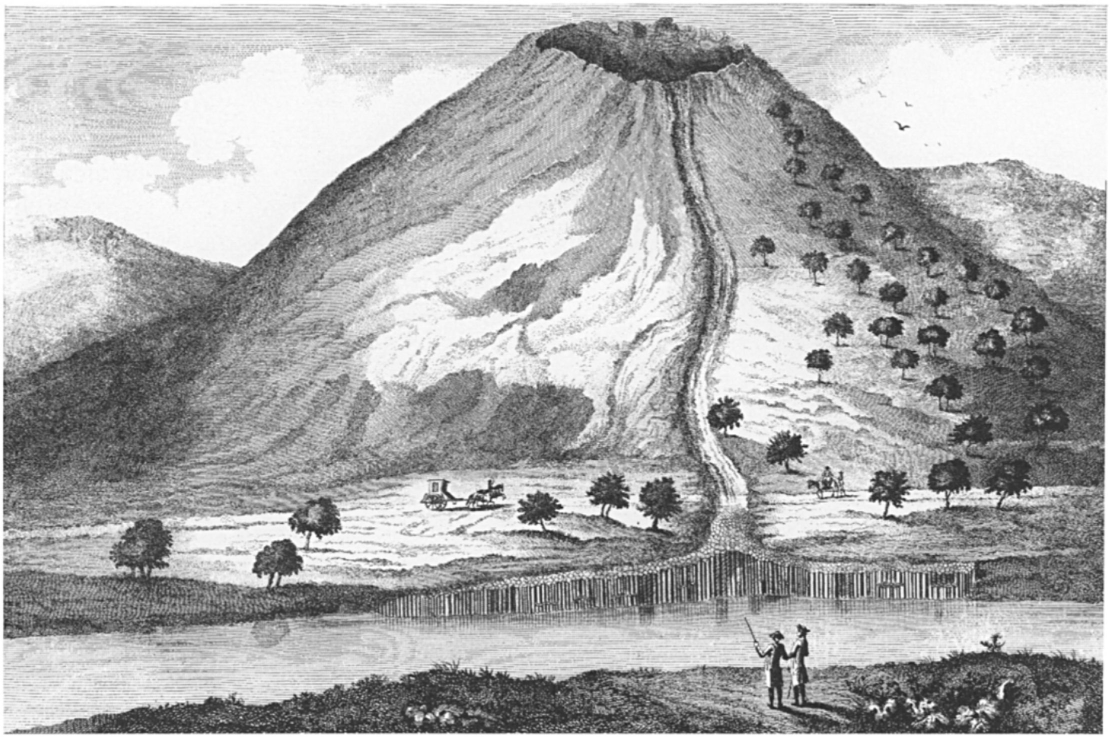
To ask about the *origins* of natural species, however, seemed as meaningless in mineralogy as in botany and zoology; or at least, such questions were often regarded as abandoning natural history for the speculative realm of metaphysics. Classifications were intended to reflect the diversity of the world; how its natural kinds had come into being was generally considered to lie beyond scientific investigation, simply because it belonged, in effect, outside time. However, it was in mineralogy that this static conception of the natural world first began to be undermined, as a result of the emergence of problems for which questions of origin seemed both appropriate and soluble.[2]

A science of fieldwork

One of the distinctions that was clarified in the eighteenth century was that between *minerals* and *rocks*. The former term took on a more restricted – and modern – meaning; rocks were interpreted as aggregrates of, usually, more than one kind of mineral. Thus granite was understood as a rock composed of crystals of minerals such as quartz, felspar and mica, and limestone as a rock composed mainly of grains of calcite. Even if the origins of mineral species were considered to be beyond the realm of natural science, the origins of composite entities such as rocks were clearly not. Many rocks, notably 'pudding-stones' (in modern terms, conglomerates or consolidated gravels) and sandstones, were said to be of 'mechanical' origin, being evidently composed of the debris of pre-existing rocks; but many others, such as granite and marble, were composed of crystalline minerals and were considered to be of 'chemical' origin. Whether a chemical origin implied crystallization from an aqueous solution or from a true melt was hotly debated: the contemporary state of chemistry made the former, stressing the chemically active role of water, seem generally the more plausible.

Questions of origin remained problematic, however, for many rocks, particularly for fine-grained ones such as basalt.[3] Significantly, in such cases evidence had to be sought outside the laboratory, in the *field* relations of the rocks. Using fieldwork, the French naturalist Nicolas Desmarest (1725–1815) demonstrated, for example, that at least some basalts – including some with the spectacular hexagonal jointing that made them look like gigantic crystals – were connected to present or former volcanoes, and must originally have been molten lavas.[4] But the field relations of other basalts, found far from any volcanoes and sandwiched between sandstones or other rocks that had clearly been sediments, later suggested to other mineralogists that basalt was a rock of sedimentary origin: this view was propounded forcefully by Abraham Werner (1749–1817), who taught at the great mining school at Freiberg in Saxony. The argument that followed, peaking in the 1790s, pitched the proponents of heat against those of water, or 'Vulcanists' against 'Neptunists'. On the specific issue of the origin of basalt, the Vulcanists eventually won the argument, mainly on the strength of the field evidence. However, most mineralogists – even the Vulcanists – considered that *most* rocks were probably of aqueous origin (though they thought the water might have been very hot and chemically active in some cases) and that volcanoes were relatively minor agents in the earth's economy.[5]

The basalt controversy was important in the long run, less because it settled the origin and classificatory position of one kind of rock, than because its resolution entailed *fieldwork* as an essential part of scientific practice. Until quite late in the eighteenth century, all three branches of natural history were still mainly indoor sciences. Travel and fieldwork were indeed considered essential, but they were undertaken primarily to collect specimens, which were then gathered indoors (or at least into a botanic garden) for



the closer work that made their study truly scientific. It was in mineralogy that this predominantly indoor culture first began to be seriously challenged.

Figure 16.3 A view of an extinct volcano in central France, with a solidified lava flow revealed at the river's edge to be basalt with prismatic or columnar jointing. The carriage indicates not only the scale, but also the means by which some gentlemanly naturalists did much of their fieldwork. From an engraving in Barthélemy Faujas de Saint-Fond, *Recherches sur les volcans éteints du Vivarais et du Velay* (Grenoble, 1778).

A science of mineral distributions

By the late eighteenth century, mineralogy was already far wider than the modern science of the same name, because it encompassed the geographical dimension of the science of the earth. Some of its most prominent practitioners, such as the Genevan naturalist Horace Bénédict de Saussure, insisted that fieldwork was indispensable, not just for collecting specimens – a task that had often been delegated to assistants or employees – but for seeing with one's own eyes how the various minerals and rock masses were spatially related to one another and to the physical topography of the areas in which they were found.[6] Added to that was the importance of witnessing for oneself the more spectacular features of the mineral world, such as erupting volcanoes and high mountains and their glaciers. Published descriptions of travels could convey only a pale intimation of the grandeur of these phenomena. Even the pictures that increasingly accompanied such texts were no more

Figure 16.4 A view by Pietro Fabris of the 1767 eruption of Vesuvius, from a hand-coloured engraving in *Campi Phlegraei* (Naples, 1776–9), Sir William Hamilton's monograph on the volcanic region around Naples. Landscapes such as this were effective proxies for the first-hand experience of the more spectacular features of the mineral world. Hamilton (now perhaps best known as the husband of Admiral Nelson's mistress Emma) was the British ambassador to the court in Naples, and used his residence there to become an outstanding expert not only on volcanoes but also on the antiquities of the region.

than proxies for the first-hand visual experience of remote or distant places; at their expensive best, however, the proxies could be remarkably vivid (Figure 16.4).

'Physical geography' or 'mineral geography' therefore became for many mineralogists the preferred name for their scientific activity. Topographical maps became indispensable tools, with which the distributions of minerals and rocks could be plotted and their spatial regularities perceived.[7] Topographical maps drew attention to river patterns and drainage basins, the location and direction of mountain ranges, the form of coastlines and the distribution of more striking features such as volcanoes; they enabled generalizations about the form of the earth's surface to be perceived and expressed. The occurrence of distinctive or useful rocks and minerals could then be plotted on a map, using conventions adapted from standard cartographic practice: either as scattered symbols, denoting outcrops or quarries, or more boldly – by extrapolation – as a patchwork of colour washes (Figure 16.5).

No mineral geographer, however, could be blind to the third dimension that – at least potentially – converted distributions at the earth's surface into structures in the earth's interior. The relative abundance of rock outcrops and other natural sections in hilly and mountainous regions, and the concentration of useful mineral resources there, focused mineralogists' attention on the hard rocks they termed 'Primary', in preference to the generally softer 'Secondary' rocks of the lower-lying regions.[8] 'Primary' and 'Secondary' denoted the relative structural position of rocks, and only sub-

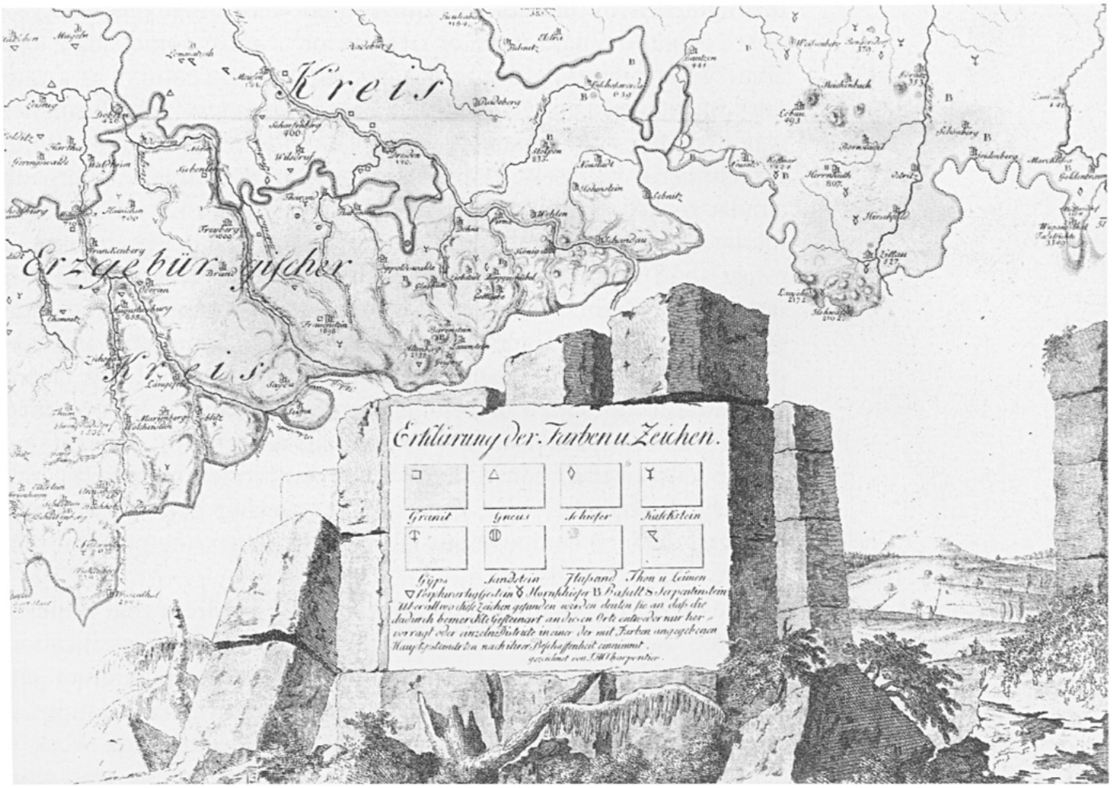


Figure 16.5 The key to a late eighteenth-century mineral map: the distributions of eight kinds of rock (granite, limestone, sandstone, etc.) are represented both by spot symbols and (in the original) by colour washes; but they are not arranged in any particular order, and the map represents a pattern of areal distribution rather than a three-dimensional structure. From the *Mineralogische Geographie* (Leipzig, 1778) of part of Saxony, by Johann Charpentier.

ordinately their presumed relative age (Primary rocks were sometimes termed 'Primitive'). The hard rocks of upland regions were 'Primary' because they appeared to constitute the foundations of the earth's crust; the softer rocks of lowland regions were 'Secondary' because they manifestly overlay the others, and were at least partly composed of their debris (although often lower in topographical position, Secondary rocks could be seen to overlie or lap against Primary ones, wherever the junction was exposed).

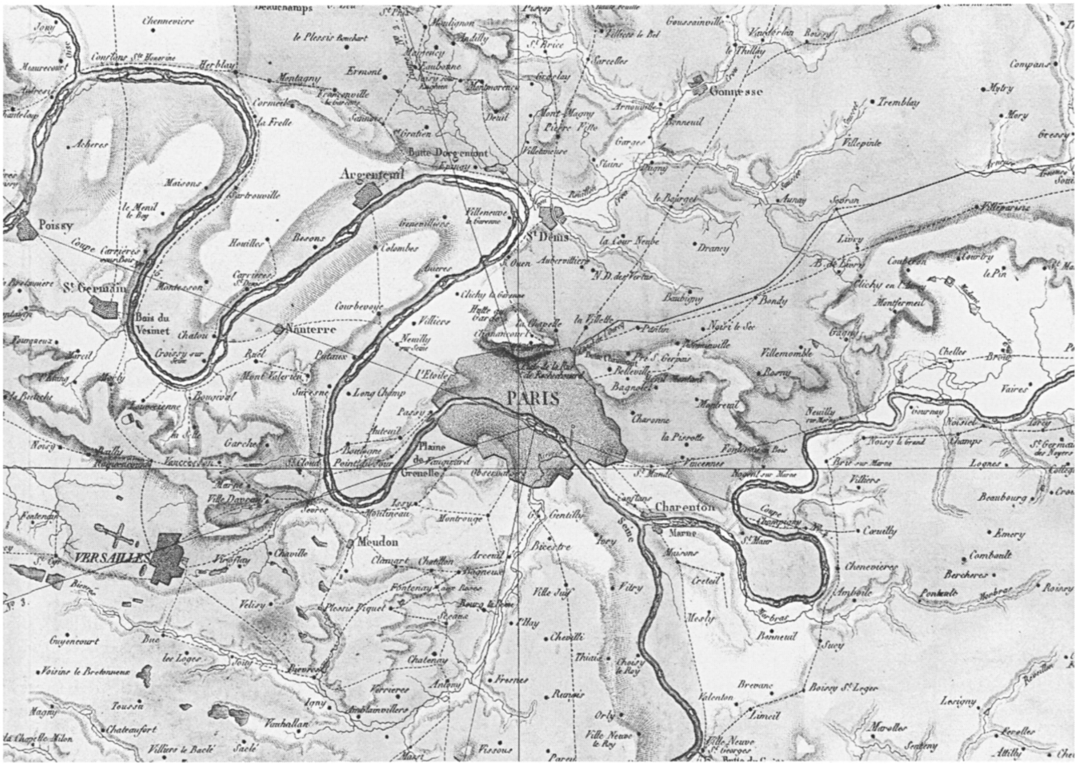
The distinction between Primary and Secondary was taken for granted in the eighteenth century, just for practical convenience of description. Volcanic rocks of any age were generally treated as another category on the same level; and 'Alluvial' was used for superficial deposits of sand and gravel (not rocks at all, in the everyday sense).

A science of rock formations

These four broad categories – Primary, Secondary, Volcanic, Alluvial – were much too general to do justice to the diversity of rocks found in many regions. On the other hand, the individual layers, beds or 'strata' (for example, specific coal seams) that were distinguished by miners and quarrymen were often not recognizable beyond a single mine or quarry, or at most some small local area. What came into use in the late eighteenth century, as a category of intermediate generality, was the *formation*.[9] The formation was a concept of immense practical value, despite the impossibility of defining it precisely. A formation was an assemblage of broadly similar rocks, separated more or less sharply from the adjacent formations; the equivalent German term *Gebirge* (literally, 'mountain range') and French term *terrain* both indicate its geographical connotations. A formation might, for example, be termed a sandstone, even if it included some intercalated strata of limestone or shale, provided it had some distinctive overall character and was clearly separated from (say) a limestone formation on one side, or above, and a shale formation on the other side, or beneath. Formations, unlike most of their constituent strata, could often be traced across country throughout some wide region, varying perhaps in thickness and detailed composition, but retaining the same position relative to other formations.

The use of the formation concept made it apparent that minerals required two distinct and complementary kinds of classification: one appropriate to specimens as analysed in the laboratory and stored in the museum, the other to the larger spatial relations of rocks observed in the field.[10] The basic and continuing work of defining, naming and classifying minerals and rocks was work centred on the examination of specimens, and it aimed to display and order the diversity of mineral 'species' and of the rocks that were their aggregates. In contrast, a classification centred on fieldwork included such categories as bed or stratum, Primary and Secondary, and – now – formation; it aimed to display the three-dimensional spatial relations of 'mineral bodies' or rock masses.

The branch of mineralogy that dealt with the classification of rock masses and their spatial relations became known as *geognosy* (literally, knowledge of the earth). The formation concept was central to its practice. Its usual form of publication was a sequential description of the formations found in some specific region. This was often accompanied by a map showing the areal extent of their 'outcrops' at the surface, and one or more sections showing their inferred relations below the surface: together, these allowed the reader to imagine the structure of the area in three dimensions (see Figures 16.6, 16.7). But 'geognosts' (as they called themselves) aimed to define and describe formations that would be recognizable beyond a single region, and ideally even on a global scale. That required a corresponding concept of *correlation*, by which a given formation was identified with its equivalents in other regions or even on other continents, even if it did not have exactly the same character everywhere.



In that task of recognizing formations in different regions, and thereby making the classification as widely applicable as possible, many different criteria were tried out empirically. The kinds of rock were always basic, but many of the same rock types – for example, sandstone or limestone – characterized more than one distinct formation. That criterion was therefore supplemented by others: for example, the altitude at which a formation was usually found, or the degree to which its constituent layers were usually tilted out of the horizontal. However, those criteria proved fallible in practice; what seemed to be the same formation might be found high on mountains in one region and at low elevations in another, or highly tilted in one region and almost horizontal in another. The criterion of 'superposition' proved more reliable: true formations, whatever their altitude or degree of tilt or folding, seemed always to retain the same relative position in the three-dimensional stack of rocks revealed in natural or man-made sections.

Geognosy embodied a primarily structural conception of mineral science. Formations were typically described as 'above' or 'below' others; it was their structural order, as three-dimensional rock masses, that seemed to be reliably invariable, even when in a given region certain formations were missing. The Prussian geognost Leopold von Buch (1774–1853), in a public lecture in 1809,

Figure 16.6 Part of the engraved 'mineralogical map' (hand-coloured in the original) illustrating the monograph by Georges Cuvier and Alexandre Brongniart on the *Géographie minéralogique des environs de Paris* (Paris, 1811). This was based on fieldwork in which the standard procedures of geognosy were supplemented by study of the abundant invertebrate fossils in some of the formations; it allowed relative ages to be assigned to Cuvier's much rarer but spectacular vertebrate fossils. The continuous lines radiating from the centre of Paris indicate the positions of a series of sections; the combination of map and sections enabled the region to be envisaged as a three-dimensional structure.

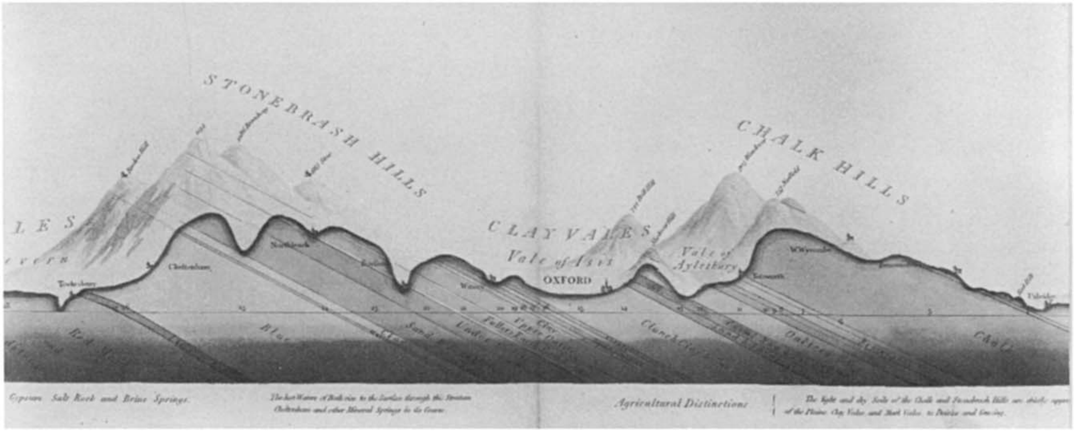


Figure 16.7 Part of William Smith's *Geological Section from London to Snowdon* (London, 1817), showing the succession of formations (in modern terms, mostly of Jurassic and Cretaceous age) in southern England. The section was intended to be 'read' in conjunction with Smith's great geological map of England and Wales (1815), to give a sense of the three-dimensional structure of the country (the 'Stonebrash' and 'Chalk' hills are, respectively, the Cotswolds and Chilterns). The vertical scale – and hence also the 'dip' of the strata – is exaggerated, in order to clarify the relations between the formations. The boundaries between them are drawn boldly with ruled lines, in a style reflecting Smith's work as a civil engineer, although this entailed major extrapolation from the evidence observable at the surface in outcrops and quarries.

explained the concept of formations by using the homely analogy of a row of houses, in which the identity and relative positions would remain unaltered even if some houses were demolished; his fellow Prussian, Alexander von Humboldt (1769–1859), later proposed an elaborate algebraic notation ('pasigraphy') to express the physical place of any formation in a putatively universal order (*Essai géognostique*, 1823). All geognosts were well aware that this structural order of position also represented a temporal order of origin, since it was axiomatic that a structurally lower formation must have preceded in origin any formations that lay above it. But this temporal element was always subordinate to the structural; geognosy was essentially a spatial science, a three-dimensional extension of mineral geography.

A science of characteristic fossils

Around the end of the eighteenth century, yet another criterion – fossils – began to be added to the practice of correlation in geognosy. The mineral specimens that eighteenth-century naturalists collected and classified included many that they considered to be of plant or animal origin. Seventeenth-century debates about the nature of distinctive mineral objects ('fossils' in the original sense) had long been resolved by settling the criteria by which those that were truly the remains of once-living beings could be distinguished from those of inorganic origin. Phrases such as 'extraneous fossils' denoted those of organic origin, but the adjectives were slowly dropping out, leaving the noun with its modern meaning.

Fossils were collected assiduously from Secondary strata, but their perceived significance was limited. The conception of them as 'extraneous' to the rocks in which they were found subtly discouraged any use of them as potential criteria for defining or identifying formations: on the ancient philosophical distinction, they seemed merely 'accidental' characters, not 'essential' ones. Fossil shells were recognized as analogous to those of living marine molluscs (see Figure 16.2); but that simply confirmed that most Secondary rocks had been deposited in the sea and that the sea must formerly have covered the present continents, which was no news to any naturalist. Above all, however, fossils were neglected because scientific attention was focused mainly on the Primary rocks, with their valuable mineral veins and spectacular mineral specimens, and they, by definition, lacked any trace of fossils.

This relative neglect of fossils in geognostic practice ended dramatically in the early nineteenth century when, from two different directions, a new attention was given to the soft and richly fossil-bearing Secondary rocks of some low-lying areas. The English mineral surveyor William Smith (1769–1839) found empirically that fossils were a highly effective means of distinguishing between otherwise similar formations, across wide tracts of the English countryside, where there were only scattered rock outcrops or quarries: specific fossils, he claimed, were 'characteristic' of specific formations. At about the same time, the French comparative anatomist Georges Cuvier (1769–1832), having been attracted to the study of *fossil* bones, realized that their relative ages could be clarified by following geognostic procedures. He and his mineralogist colleague Alexandre Brongniart (1770–1847) augmented that practice, however, by giving close attention to the fossil shells found abundantly in some of the formations around Paris: in their work the fossils became 'essential' features of the formations. Maps and sections, and lists or pictures of the relevant fossils, were published both by Cuvier and Brongniart (1808–11) and by Smith (1815–19).

The priority dispute that ensued had nationalistic overtones – not surprisingly, since France and Britain were at war until 1815 – but the end result was simply to equip geognostic practice internationally with a powerful new tool for correlation. Fossils proved to be generally – though not invariably – reliable indicators of equivalent formations, not only within a given region but also internationally and even globally. The 1820s and 1830s saw the widespread application of the new fossil-based methods to Secondary rocks in many parts of the world; by about 1840 geognosy had been transformed by the empirical success of the fossil criterion.

A standard sequence of formations, now assembled into still larger groupings or 'systems' (for example, 'Carboniferous' and 'Cretaceous'), had been accepted consensually as being valid throughout Western Europe, the most thoroughly explored part of the earth's surface. Its limits were being extended to the Russian empire and to North America, and tested in still more remote

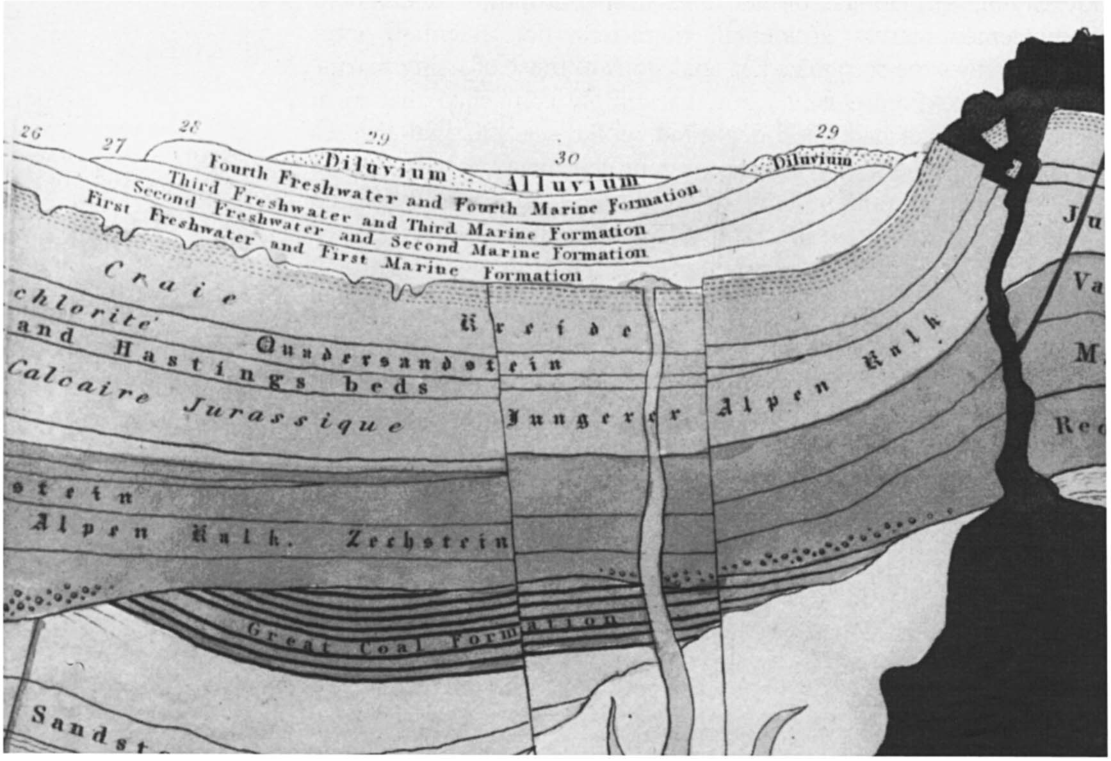


Figure 16.8 A portion of the large generalized or 'ideal section' that illustrated the popular *Geology and Mineralogy* (London, 1836) by the English geologist William Buckland, showing part of what was by then an internationally accepted sequence of major formations of sedimentary rocks (note the French names in italics and German ones in Gothic); igneous or volcanic rocks erupt from the depths. The 'Diluvium' was the peculiar 'boulder clay' or 'till' that was generally attributed to the most recent 'catastrophe'; the 'Alluvium' was the still more recent material (e.g. river gravels) from the human epoch; note the minor role of both in the whole sequence of formations, and hence implicitly the vast scale of *pre-human* earth history. Far thicker formations (not shown in this part of the section) underlay the 'Great Coal Formation' and represented even earlier periods of the earth's history.

regions throughout the world. Even the rocks that Werner had called 'Transition', in which fossils were usually rare or poorly preserved, were yielding to the same treatment (giving rise, for example, to 'Silurian' and 'Devonian'); this pushed the sequence of systems down towards the Primary rocks.

Such descriptive work – later termed 'stratigraphy' – became the foundational practice of what was now almost universally called 'geology'. It was carried out both by gentlemanly 'amateurs' – whose work was anything but amateurish – and by a new and growing breed of professional geologists. The latter were now to be found not only in the management and administration of mines, but also in the new 'geological surveys' instituted and financed by governments in many parts of the world. The first state-supported survey was in France: a team of three geologists began work, significantly, by visiting England in 1823 to study the methods that by then were standard among the members of the Geological Society of London.[11] By 1834 their geological map of France was virtually complete. In the British political climate, less hospitable to state intervention of any kind, an analogous survey started in a precarious and *ad hoc* manner in 1832, but was not established on a permanent basis until the end of the decade. By that time some of the states of the USA had also founded surveys, spreading the model beyond Europe.

Stratigraphical geology remained as structural in orientation as the geognosy from which it had developed. Of course, it provided a basis for a historical understanding of the earth and of life at its surface, but it was not itself primarily historical. Formations continued to be described as 'above' or 'below' one another far more often than they were said to be 'younger' or 'older', and the focus continued to be on their three-dimensional relations as rock masses. Likewise, the study of formations remained as thoroughly descriptive in character as the natural history that had been its origin; it provided materials for causal inferences about the earth and its life; but it was not itself primarily a causal science.

A 'theory of the earth'

Historical and causal analyses of the earth belonged to a different intellectual tradition, which in the late eighteenth century was regarded as distinct, even by those who aimed to contribute to both; only gradually, in the early nineteenth century, did it merge with the descriptive tradition. Mineralogy, mineral geography and geognosy were all regarded as branches of descriptive natural history; theorizing about the history of the earth and its causes, on the other hand, belonged to 'natural philosophy' or, in the old broad sense of the word, to 'physics', the science of natural causes.

Ever since the seventeenth century, causal and historical interpretations of terrestrial phenomena had been termed 'theory of the earth', and in the eighteenth century many important works bore that title. The phrase denoted not so much any particular theory, but rather a genre in which a set of initial conditions (for example, the earth as a molten globe) was coupled with a set of physical principles (for example, the laws of cooling bodies), and used to generate a hypothetical sequence of events or stages through which the earth might have passed in reaching its present state.[12] The *Theory of the Earth* by the Scottish 'natural philosopher' James Hutton (first published in 1788, enlarged into book form in 1795) was a late example of the genre; by the time it appeared, the sheer proliferation of such theories, with each author proudly expounding his own and emphasizing its originality, was leading to a reaction against such unconstrained causal speculation. Saussure, for example, was prominent among those who argued that the variety of these theories proved that all were premature, because they were too little constrained by observational evidence. So when in 1779 Jean-André Deluc (1727–1817), a Genevan resident in England, proposed the word 'geology' (in a mere footnote!) as the terrestrial counterpart of cosmology, it was correctly taken to be a synonym for 'theory of the earth', and was therefore treated with caution or even rejected outright.

Only in the early nineteenth century did the word 'geology' begin to lose its speculative connotations, as 'geologists' – as they then began to call themselves – recognized that more restricted kinds of causal interpretation might be legitimate. The changing status of the word is signalled by its adoption in 1807 by the first scientific society specifically for the study of the earth (the Geological Society of London), notwithstanding its founders' explicit rejection of 'theory of the earth' and strong emphasis on the value of collecting 'facts'. By 1830, when the similar Geological Society of France was founded in Paris, the word had completely lost its earlier dubious reputation, and was used in its modern sense.[13]

One of the earlier overarching theories, however, gave the science a conceptual legacy that transcended its genre. In *Les Epoques de la nature* (1778), the great French naturalist Georges Leclerc, comte de Buffon (1707–88), postulated an initially molten globe that had gradually cooled to its present state. The theory itself was based on little fieldwork, and was widely regarded as outmoded even when published; but the elegant text embodied metaphors that were powerfully influential, although not original to Buffon. His hypothetical story was divided into the six 'epochs' of his title, and he referred to features such as extinct volcanoes and the marine fossils found high above sea-level as the 'archives' or 'monuments' of nature, because they could be regarded as relics surviving from some former state of things. The language of 'epochs' was quickly adopted by others such as Desmarest, but in the service of more modest and local interpretations.[14] Likewise, natural features were used increasingly as evidence for reconstructing an earth history which – because it was ultimately contingent – could *not* be predicted in advance on the basis of any overarching theory. It is no coincidence that this matched the contemporary use of human archives and monuments by historians and antiquarians, in the service of a new historicism, in place of an earlier and deductive style of 'conjectural history'. As with the human world, the diversity of the natural world began to be historicized: a static 'natural history' of the earth began to turn into a truly temporal *history* of the earth.

A science of the history of nature

This newly historical element was evident (as in Desmarest's work) even before geognosy was transformed by the addition of the fossil criterion; but the new attention given to fossils from around the turn of the century greatly accelerated the change. Large bones, apparently those of elephants and other tropical mammals, had long been found in relatively cool climates and high latitudes in both Old and New Worlds. But only in the 1790s did Cuvier's careful study of these bones decisively confirm earlier suspicions that they belonged to species that were distinct from any living mammals and probably extinct. That in turn made it seem more plausible that many fossil shells – far more common than any bones – also belonged to truly extinct species, and not, as had until then seemed possible or even probable, to species still lurking alive in the unexplored depths of the ocean.

With that growing belief in the generality of extinction, it made sense to treat the 'characteristic' fossils of the various formations as being indeed 'essential' to them; for they now became indices of unrepeatable *historical* change, as well as of repeatable environmental conditions. Cuvier's and Brongniart's joint study of the formations around Paris (1808–11) was accepted immediately as a decisive exemplar of a new practice that combined the older geognostic framework with a newly historical and causal dimension. Unlike Smith's rival work on the English formations, with its purely empirical use of the fossil criterion, the French study treated both formations and fossils as evidence for a truly historical interpretation of the Paris region: in terms both of a changing environment – an alternation of marine and freshwater conditions – and of a unique and irreversible history of life.

At much the same time, Cuvier transformed the concept of the earth's 'revolutions' – until then simply a vague notion of major changes in the past – into a much more concrete argument: that *some* (not all) such changes had been 'catastrophes', or sudden changes in environment, which could have caused the extinctions he claimed. Like most of his contemporaries, Cuvier rejected the older style of 'theory of the earth' as premature, and prudently abstained from suggesting what might have caused the sudden catastrophes. But he also rejected the widespread view that the 'actual causes' currently at work in the world were adequate to have produced all the effects observed.[15] The subsequent controversy led geologists in the 1820s to examine much more closely – either by direct field observation or by analysing

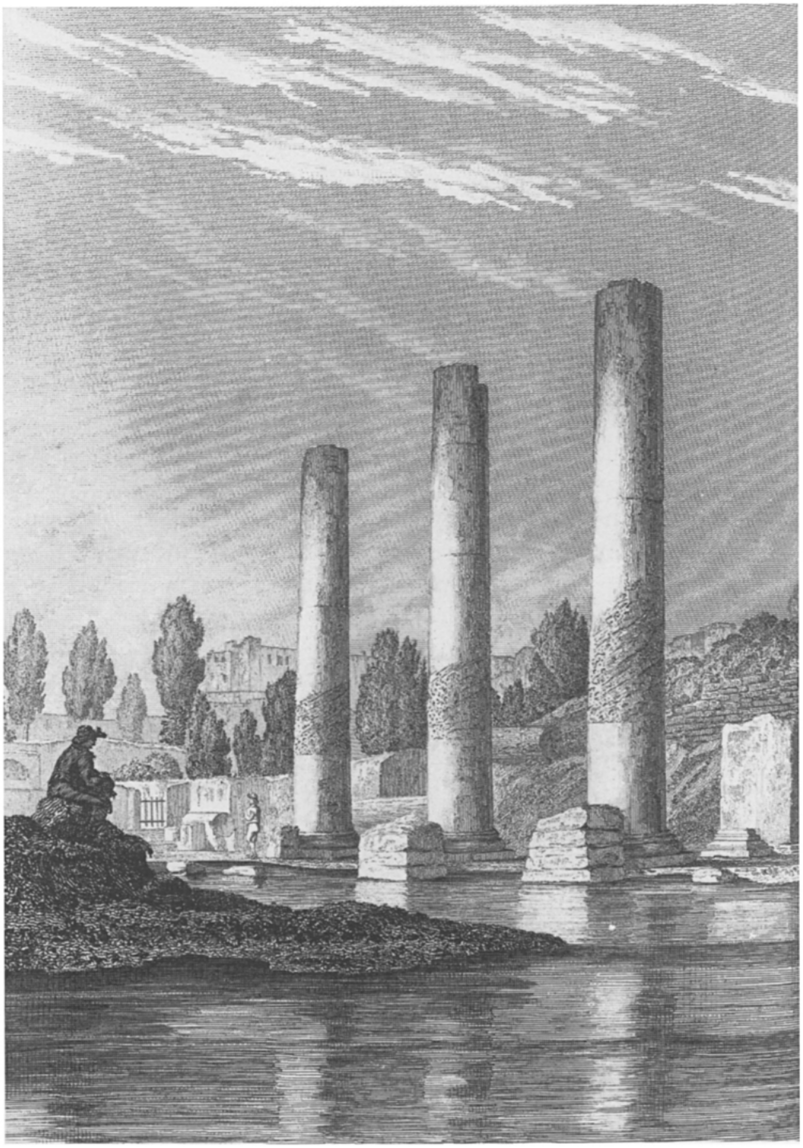


Figure 16.9 The frontispiece to Charles Lyell's *Principles of Geology* (London, 1830). This engraving of the surviving columns of the 'Temple of Serapis' near Naples deliberately symbolized Lyell's claim that all the natural 'monuments' of past events can be attributed to the action of processes no more catastrophic than those that are directly observable or recorded in human history. Although the temple (probably in fact a market) was built on dry land in Roman times, a later submergence was recorded by the borings of marine molluscs part way up each column; yet at a still later time the ruin had been elevated back to its modern position at sea-level. This epitomized Lyell's theory of non-directional or steady-state earth history; it suggested how a long succession of similar small-scale changes could have produced even the elevation of mountain ranges and the subsidence of continents, given enough time; and it neatly integrated geological with human history, and past with present, by using a human monument as a witness to geological change.

historical records – just what those agents *were* capable of effecting.

Developing that tradition, the London geologist Charles Lyell (1797–1875) argued persuasively in his *Principles of Geology* (1830–3) that the power of 'actual causes' had indeed been underestimated, and that much geological change had been very gradual, or at least, no more violent than the natural events and processes recorded in human history (Figure 16.9). 'Catastrophists' and 'uniformitarians', as they were called in the 1830s, were never sharply separated parties, and by around 1840 they had in practice reached a kind of compromise: most geological features were agreed to be the work of agencies still observable in the present world, such as sedimentation, erosion, vulcanism and crustal elevation; but it was widely believed that these processes might have slowly declined in their intensity, and might have been much more powerful in the distant past.

A compromise seemed inescapable, because some phenomena continued to resist Lyell's kind of explanation. The peculiar features (erratic blocks, till or boulder clay, etc.) that had been attributed to the most recent catastrophe were particularly puzzling, because no 'actual cause' seemed adequate to account for them. Cuvier had equated the most recent catastrophe with the flood recorded obscurely in the ancient records of many human cultures. His English follower William Buckland (*Reliquiae diluvianae*, 'Relics of the Deluge', 1823) accentuated its identification with one such record – the 'Deluge' of Genesis – and termed the deposits 'Diluvium' (see Figure 16.8). But in practice the 'geological deluge' was conceived as an event very different from any literal reading of Genesis. Its later transformation into an 'Ice Age', due mainly to the Swiss naturalist Louis Agassiz's *Études sur les glaciers* (1840), finally severed any such connection, for all but the scientifically marginal 'scriptural geologists' (mainly in Britain and North America). Above all, however, the acceptance of some kind of glacial period in the geologically recent past served to confirm that the earth had had an unexpectedly eventful history.[16]

A history of earth, life and man

By around 1840 most geologists conceded in practice that the course of earth history could not be predicted in advance by any grand theory – neither by Lyell's steady-state theory nor by the more generally favoured theory of a gradual cooling – but only reconstructed by detailed analysis of the organic and inorganic 'archives of nature'. That conclusion was embodied most strikingly in the first tentative attempts to represent in pictorial form what the world might have looked like in that remote pre-human past (Figure 16.10). It was embodied more formally in the proposal in 1840, by the English geologist John Phillips (1800–74; the nephew of William Smith), that the whole history of life could be summarized in three great eras, the Palaeozoic, Mesozoic and Cenozoic (the eras of ancient, intermediate and recent kinds of animals). With such terms, the historicization of the older geognostic classification of formations and systems was in principle complete.

That this immensely long and complex history was almost entirely *pre-human* was a conclusion that was transformed in these same decades from conjecture to consensus. Back in the late

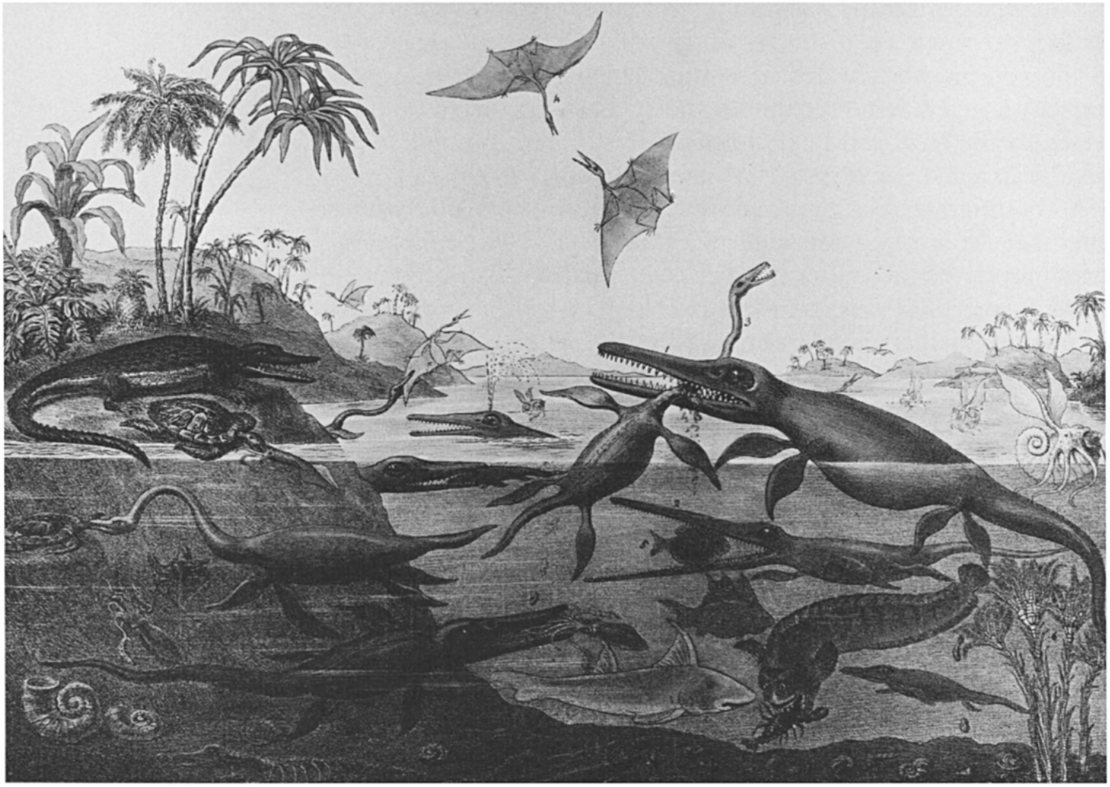


Figure 16.10 'A more ancient Dorset': a view of life at a remote pre-human period (in modern terms, Jurassic), as drawn by the English geologist Henry De la Beche and lithographed by the artist George Scharf (1830). This was one of the first true pictorial reconstructions of extinct animals, based on a detailed analysis of well-preserved fossils and showing them in their inferred habitat. Large-jawed ichthyosaurs, thin-necked plesiosaurs and flying pterodactyls (in modern terms, pterosaurs) are the most prominent animals. Such imaginary landscapes were quickly adopted for popular books, and served to make the new earth history vividly real to a wide public.

eighteenth century, Buffon's seventh and human epoch (added only shortly before publication) made explicit a speculation already widespread among naturalists: that the whole of human history was but a brief final chapter in a far longer story, recorded in the thick sequences of fossil-bearing Secondary rocks. Buffon's total time-scale of tens of thousands of years – based on scaling up the results of experiments with cooling model globes – was modest by later standards; but it was quite vast enough to be, in a literal sense, almost unimaginable. In the subsequent decades, quantitative estimates of geological time were rarely made explicit, simply because there was little concrete evidence to base them on, and they were widely regarded as merely speculative. But the practice of geologists leaves no doubt that by around 1840 they had surmounted the imaginative hurdle of thinking about vast expanses of time, as successfully as astronomers had become accustomed to thinking about the vast expanses of space.

Geologists' estimates of time were, of course, far too large to be compatible with the traditional chronologies derived from a literal reading of Genesis. However, such literalism had already been discarded by most savants or 'men of science', whether they were personally religious or not, chiefly as a result of the development of scholarly biblical criticism. After the mid-eighteenth century, no major naturalists were seriously hampered by ecclesiastical criticism, still less by persecution, on account of the time-scales they proposed. Buffon, for example, received only the most perfunctory criticism in 1778 for his *Epoques*, in contrast to that which had greeted his earlier theory of the earth in 1749. After the turn of the century the relation between geology and Genesis became a marginal issue for geologists, except for the public relations of their science, and even then only locally (mainly in Britain and North America).

What was more problematic was the relation between the complex history of the earth and its life, as it was reconstructed with increasing confidence and precision by geologists in the early nineteenth century, and the far shorter span of human history, as it was extended backwards by analysis of ancient documents (of which Genesis was only one). Both natural and textual sources continued to be deployed in conjunction with one another, as in Cuvier's and Buckland's work, because both seemed relevant to what was now perceived as a single *history*. Until after mid-century, however, the two sources proved extremely difficult to integrate: the fossil traces of early human life remained sparse and highly problematic, and the concept of a long human 'pre-history' preceding any literate civilization was slow to gain acceptance.[17]

Conclusion

The practice of mineralogy first began to diverge from that of botany and zoology when its problems demanded a geographical, distributional or spatial dimension, and therefore a heightened emphasis on fieldwork. That practice then became increasingly three-dimensional or structural in character, and developed into 'geognosy', the study of rock masses or 'formations' and their world-wide correlation. Geognosy in turn was transformed (into what was later termed stratigraphy) by the striking empirical success of the new criterion of fossils. Initially distinct from all such descriptive practices was the causal project of 'theory of the earth', which aimed to model the likely course and causes of the earth's temporal development. This did not become truly historical, however, until its deductive style was abandoned: its concepts of nature's 'epochs', and of specific features as nature's 'archives', were absorbed into a more inductive and contingent style, by being combined with the newer fossil-based geognosy. By about 1840, a long and complex earth history, dwarfing the whole of subsequent human history, had become a consensual feature of the scientific view of the world.

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