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History of sciences

Charles Lyell and scientific thinking in geology

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Abstract

Charles Lyell (1797–1875) was born at Kinnordy, Scotland. His father, an amateur botanist, and his grandfather, a navigator, gave him very soon a taste for the observation of the Nature. He went to the Oxford University to study classical literature, but he also followed the geological course of William Buckland. After having been employed as jurist for some years, in 1827 he decided on a career of geologist and held the chair of geology of the King's College of London, from 1831 on. He was a contemporary of Cuvier, Darwin, von Humboldt, Hutton, Lavoisier, and was elected 'membre correspondant' of the 'Académie des sciences, France', in January 1862. Charles Lyell is one of the eminent geologists who initiated the scientific thinking in geology, in which his famous volumes of the *Principles of Geology* were taken as the authority. These reference volumes are based on multiple observations and field works collected during numerous fieldtrips in western Europe (principally Spain, France, and Italy) and North America. To his name are attached, among others: (*i*) the concept of uniformitarism (or actualism), which was opposed to the famous catastrophism, in vogue at that time, and which may be summarized by the expression "The present is the key to the past"; (*ii*) the division of the Tertiary in three series denominated Eocene, Miocene, and Pliocene, due to the study of the age of strata by fossil faunas; (*iii*) the theory according to which the orogenesis of a mountain chain, as the Pyrenees, results from different pulsations on very long time scales and was not induced by a unique pulsation during a short and intense period. The uniformity of the laws of Nature is undeniably a principle Charles Lyell was the first to state clearly and to apply to the study of the whole Earth's crust, which opened a new era in geology. ***To cite this article: C. Virgili, C. R. Geoscience 339 (2007).***

Résumé

Charles Lyell et la pensée scientifique en géologie. Charles Lyell (1797–1875) naît à Kinnordy, en Écosse. Son père, botaniste amateur, et son grand-père marin lui donnent très tôt le goût de l'observation de la Nature. Il entre à l'université d'Oxford pour y étudier la littérature classique, mais y suit en même temps les cours du géologue William Buckland. Après avoir exercé quelques années la profession de juriste, il s'oriente définitivement, en 1827, vers la géologie, et il occupera la chaire de géologie du King's College de Londres à partir de 1831. Contemporain de Cuvier, Darwin, von Humboldt, Hutton, Lavoisier, il est élu, en janvier 1862, membre correspondant de l'Académie des sciences de France. Charles Lyell est l'un des grands géologues initiateurs de la démarche scientifique en géologie, matière en laquelle ses célèbres volumes des *Principles of Geology* font autorité. Ses ouvrages reposent sur d'innombrables observations et faits de terrain, recueillis au cours de nombreux voyages sur le terrain en Europe de l'Ouest (principalement en Espagne, en France, en Italie) et en Amérique du Nord. À son nom sont attachés, en particulier : (*i*) le concept d'uniformitarisme (ou actualisme), opposé au catastrophisme, très en vogue à l'époque, et qui peut se résumer par l'expression « Le présent est une clé pour comprendre le passé » ; (*ii*) la division du Tertiaire, grâce à l'étude de l'âge des strates par les faunes fossiles, en trois séries dénommées Éocène, Miocène, Pliocène ; (*iii*) la théorie selon laquelle la formation d'une chaîne

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de montagne, telle celle des Pyrénées, se déroule sur de longues périodes et est le fruit de différentes pulsations successives et non pas d'une unique pulsation brusque. Il est indéniable que l'uniformité des lois de la Nature, un principe que Charles Lyell est le premier à avoir énoncé clairement et à avoir appliqué à l'étude de l'ensemble de la croûte terrestre, a ouvert une ère nouvelle de la géologie. ***Pour citer cet article : C. Virgili, C. R. Geoscience 339 (2007).***

Keywords: History of geology; Lyell; Uniformism; Actualism; Catastrophism

Mots clés : Histoire de la géologie ; Lyell ; Uniformism ; Actualisme ; Catastrophisme

1. Introduction

In the 17th century, modern science began and Newton showed in *Philosophiae naturalis principia matematica* [26] that the movements of astral bodies are governed by a set of laws and that their movements can be calculated. Therefore, the universe can be understood through the application of reason. In 1789, the year of the French Revolution, another revolution occurred in the field of science. With the publication of the *Traité élémentaire de chimie* by Antoine-Laurent de Lavoisier [20], the new science of Chemistry, which for years had been the domain of the alchemists, was consolidated.

In geology, the situation was different. The 'laboratory' of the geologist is outdoors, in the mountain ranges, the plains, the glaciers, the deserts . . ., but the fundamental problem is the time scale during which terrestrial phenomena occur, the Earth' time scale being completely different from the human time scale. Chronicles and accounts record human history, but it is not easy for our minds to imagine a world before ours, with no one to observe it and transmit observations. Myths and religion have carried out this function for centuries and so, while physicists and chemists dedicated themselves to scientific study, geologists found the explanations for the history of the Earth in the Bible and interpreted marine deposits on the continents as proof of The Great Flood.

2. Newton's model in geology

The scientific method was not applied systematically to geology until the mid-nineteenth century, when a British barrister, Charles Lyell (1797–1875), hung up his robe, picked up a hammer, and started what was to be a milestone in geology (Fig. 1). Twelve editions of the resulting book – *Principles of Geology* [23] – were published, more than a hundred thousand examples were printed in Britain and the USA, and it was translated into several other languages. The book endeavours to explain the processes that formed the materials, structures and relief of the Earth in past ages through the observation and analysis of processes that can be seen in the present. This concept is called *uniformitarianism* and is summarized by the expression ''The present is the key to the past.'' This is another way of expressing the principle put forward by Newton in 1687. ''The uniformity of the laws of Nature throughout time'' is the paradigm on which historical geology is based.

3. The beginnings of geology

In the same way, when stating that modern science began with Newton, we do not ignore the scientific contribution of Galileo, Kepler and many others, neither can we deny that when we associate the beginning of ''scientific thinking'' in geology with Lyell, there had been contributions of unquestionable quality before the publication of his. In geology, as has happened many times in the history of intellectual endeavours, technol-

Fig. 1. Charles Lyell around 1836. Drawing by J.M. Wright. National Portrait Gallery, London [39].

Fig. 1. Charles Lyell vers 1836. Dessin de J.M. Wright. National Portrait Gallery, Londres [39].

ogy or practical experience preceded scientific elaboration. The Industrial Revolution and the subsequent rise in value of certain raw materials, especially iron and coal, contributed to advances in mining technology and mineralogy. Furthermore, new public works such as roads, railways, and irrigation and navigation canals demonstrated the need to know the characteristics of the subsoil and to establish a geological cartography. As a result, the first works and schools of geology appeared in the more industrial regions, which, at the time, were concentrated in Great Britain and Central Europe.

The most important of these schools was the Freiberg School of Mining in Prussian Silesia. Abraham Gottlob Werner (1749–1817) studied there before completing his studies in Leipzig, and returned to Freiberg as director of the school. He was considered an excellent teacher and was internationally acclaimed. During 40 years, the majority of European geologists were tutored by Werner before going on to work in different countries. This explains the great diffusion of his ideas and theories, despite having published very few of them. Werner was a man of laboratory and, from the study of minerals and rocks, he wanted to construct a global model that would provide a rational explanation for the formation of the Earth, without troubling himself in the validation of his theories in the field. His contribution was the concept of imagining the Earth as being formed by successive layers (''like an onion'', as his critics suggested). The idea was not exact, but it provided a model which was closer to reality than any previous one [38], and he believed that all the rocks, included granite, gneiss, and basalts are sediments of a universal ocean, that had covered the Earth.

In England, the interest in the composition of the subsoil was not only related to mining activities (principally coal), but also to the construction of navigation canals, which were being built to allow transport to the industrial centres. William Smith (1769–1839), a topographer who specialized in the construction of these canals in the Southeast of England, decided to apply the same study techniques of the materials in the coalmines to the excavations for the canals [41]. He decided that this information could be represented on a map [30,31]. Biostratigraphy and geological cartography were born with the work of this self-educated geologist. Lyell had no contact with him until the last years of Smith's life, when his merits were finally acknowledged by the academic community and the Geological Society, where his work had not been recognized until that time, although Lyell had seen Smith's maps when he was a student of W. Buckland, who had always appreciated and valued Smith's work.

Geology in Great Britain developed outside the influence of the universities. The most important British geologist of the 18th century, James Hutton (1726–1797), lived and worked in Edinburgh, but the only contact he had with the university was during the years when he was a student there. He was nearly sixty when he presented his first results at the Royal Society of Edinburgh, which were published in the Society's Report [18]. In his *Theory of the Earth* Hutton worked from principles which were very different to those of Werner. He proposed that granite and gneiss had been formed by the consolidation of magma, and that the basalts were the result of the consolidation of ancient volcanic lavas. In 1795, two years before his death, he sent to press the first two volumes [19] of a work that was supposed to consist of four volumes: *Theory of the Earth, with proofs and illustrations.* Hutton affirmed that the Earth had a long history, whose beginning or end could not be known, and furthermore could not fit in the chronology of the Bible. However, above all, he insisted that in the past, as well as now, all geological processes are produced by the action of four sources of energy: gravity, the Earth's rotation, the heat of the sun and the internal heat of the Earth. He thus secularized geology by dispensing with ''mysterious catastrophes'' and ''divine intervention'' to explain the formation of seas, continents, mountain ranges, and valleys. He was the precursor of *Uniformitarianism* and died in Edinburgh in 1797, the same year in which Lyell was born a few miles away, as if destined to pick up and continue Hutton's work.

In France, the development of the science of geology was linked to the progressive and enlightened spirit, which is manifested in the *Encyclopédie, ou dictionnaire raisonné des sciences, des arts*... (1751–1780), and was consolidated thanks to the support of the scientific institutions during the Napoleonic period. Due to this and the genius of Georges Cuvier (1769–1832) [34], a school of palaeontology emerged, which created the indispensable bases for both biostratigraphy and approach to the study of the evolution of living species later formulated by Darwin. In the words of Lyell (*Principles of Geology*, vol. 1, pp. 72–73, [21]), ''*Inquiries were at the time prosecuted with great success by the French naturalists, who devoted their attention to the study of organic remains... This branch of knowledge has already become an instrument of great power in the discovery of truths in geology, and is continuing daily to unfold new data for grand and enlarged views respecting the former changes of the Earth.*'' Lyell became immersed in French culture and the spirit of the Enlightenment. He was aware of and valued the works of Voltaire, although he did not share his anti-religious views. He had visited France first in 1818 with his family and he had always a very good relationship with France. At 1862, he was elected Corresponding Member of the Academy of Sciences of Paris.

The first important scientific work that Lyell carried out in 1823 was the study of the Tertiary of the Paris Basin, in collaboration with C. Prévost (1787–1856), a French geologist. This study, completed with the observations in the Tertiary of the South of France and Italy made in 1828 and 1829, and the palaeontological analysis made by Deshayes (1795–1875) allowed him to define and characterize the Eocene, Miocene, and Pliocene, which would not have been possible without the previous work of Cuvier. But, at the same time, Lyell and Prévost were able to demonstrate that the limit between the three units did not correspond to the 'catastrophes' advocated by the illustrious master, but rather to a gradual change in the sedimentary environment. At the beginning of 1828, he saw the geological map of the volcanoes of Auvergne published by N. Desmarest [12] and was fascinated by its quality and by the relation it depicted between the lava flows, the volcanic cones, and the morphology of the valleys. This work determined the start of a long journey (May 1828–February 1829) in France and Italy that would precede the publication of the first volume of the *Principles of Geology.* Influenced by this scientific and cultural background and experience Lyell established the scientific method in geology, different from that of Physics or Chemistry, which seeks to prove theories and working hypotheses by the observation of reality and experiments whenever possible, instead calling upon 'catastrophes' or 'causes' that cannot be observed or subjected to valedictory criteria. He applied the Newtonian principle according to which the natural laws have remained constant throughout time. This 'invariable truth' allows us to explain the geological processes of the past that manifest themselves through the characteristics of the materials from other geological epochs, and, analyzing the processes acting today, we can reveal the history of the Earth. This is the fundamental sense of Uniformitarianism or Actualism, as proposed by Lyell, which continues to be valid.

4. Actualism, uniformism, uniformitarianism

Lyell never used any of these three words, they do not appear in any of his books or other publications; they were later attributed to him by other commentators, while either defending or rejecting his theories. It is important to remember that while English-speaking geologists always use the term 'uniformism' or 'uniformitarianism', considering them practically equivalent, continental Europeans (as the British refer to French, German and Spanish for example) use the term 'actualisme', 'aktualismus', or 'actualismo'. This is because in English the adjective 'actual' has a different meaning from the same word in Romanic languages, where it can be translated as 'current' or 'present'. In English, 'actual' means 'real', 'authentic', 'true', and it was in this sense that Lyell used the word in his publications. Lyell only accepts as causal agents of the transformations that the Earth has suffered throughout time those which the philosophers of the day called 'vera causa', and he refers to as 'actual causes' (the misinterpretation of which has caused much confusion due to the reasons previously explained), in the sense that they are observable empirically as opposed to those imagined or supposed [4,5,14,16,17].

One of the most precise (although not always exact) commentaries on the thoughts of Lyell is by the American palaeontologist Stephen Jay Gould [15]. He correctly separates the concept of *uniformitarianism* into two different meanings: *Methodological uniformitarianism* (of the laws and processes of nature) and *Theoretical uniformitarism* (of the intensity of the processes and the state of the Earth).

4.1. The uniformity of the laws of Nature

The uniformity of the laws of Nature cannot be demonstrated, it is a *postulate* or 'the rules of the game', in the same way as 'the rationality of the real world', or the fact that our reason is adequate to understand and explain the world that surrounds us. If we do not accept this, then science is impossible and everything must be left to the whims of the gods. Lyell recognized his debt to Hutton, but it was Lyell who first put forward this principle clearly and concisely, and applied it to the study of the Earth's crust, and so it is correct to affirm that scientific geology began with the work of Lyell. In an address to the Geological Society in 1831, Sedgwick, the president of the Society stated: "because thanks to him we all accept that the fundamental laws of nature are immutable, and that we can only judge the result of the processes of the past by those which we can observe while they occur." This declaration opened a new era in geology.

4.2. The uniformity of the processes

The uniformity of the processes is a consequence of the previously stated principle. Philosophers call it *the* *principle of simplicity*: one should not invent unknown or extraordinary causes if the usual known procedures are sufficient. If a sandstone has a crossed lamination analogous to what we observe in aeolic sand dunes, we know they were deposited by the wind, and if its structure and texture are analogous to those of the sand on beaches, then it is coastal sediment. Lyell's statement is categorical and emphatic: *The present is the key to the past.* We use the *key* both to unlock the secrets of the Earth and to decipher the code contained in the sediments, the rocks, and the fossils. The Earth's past is only available to us by understanding the current processes. This methodological principle converts the stratigraphic series into an archive of the Earth's history.

4.3. The uniformity in the intensity of the processes or gradualism

It is not a methodological rule, but a theory that must be demonstrated. Its formulation, correctly rejected by the majority of geologists, is the following: "the same forces exist permanently, and silently like the passage of time, have always caused slow but universal effects"; this affirmation was never made by Lyell, but by some of his followers. The discussion about whether the rhythm, velocity, and intensity of the geological processes have been variable or constant throughout the history of time, and to what degree, is a debate that began early in the 19th century and continues today. Those who measured the age of the Earth in thousands of years had to resort to intense and widely spread cataclysms in order to explain the formation of mountain ranges that were only possible in the early stages of the Earth's evolution, due to the high energy and temperatures left over from its original molten state. They contrasted the early stages of a tempestuous Earth with the current mature state, where it has settled into stability. Lyell's vision of the world was very different. He maintained that the time the Earth had required to evolve to its current state, to model the mountains and valleys, was enormous, incalculable. (We should remember that, in those days, it really was 'incalculable'; only the 'clock' of radioactivity, which would not be discovered until many years later, is capable of measuring it). In this case, it was not necessary to resort to cataclysms that in a short time would have produced great changes; weaker forces, acting slowly over long periods of time, were sufficient to explain them. He also maintained that the dynamic of the Earth has not lessened over time, as it has an 'internal energy'. This was a brilliant intuition that the later discovery of deep radioactive processes would confirm and explain. Lyell has been criticized for his supposition that in the history of the Earth everything occurred at a slow and uniform pace, in a succession of cycles that repeat themselves indefinitely without advancing in any direction [15,16]. It is true that in his early works he puts more emphasis on the slowness and uniformity of the phenomena in an attempt to refute the theories of 'catastrophes', but it should also be remembered that he was one of the principal supporters of Darwin and of his theory of organic evolution. This evolutive idea ended up pervading his vision of the history of the Earth, as can be seen in the tenth and successive editions of *Principles of Geology* [24].

4.4. The uniformity of state or antiprogressism

This supposes that there is no vector of progress and that, although details are modified, nothing really changes. This hypothesis has been attributed to Lyell, and it was probably his opinion between 1829 and 1830, when he was preparing the first edition of the first volume of *Principles of Geology.* This *uniformity of state* or *antiprogressism* was an-historic, that is to say that, rather than to deny the historical process of development, it was ignored. It was based on the assumption of a non-vectorial cycle, like the succession of seasons or the alternating climatic cycles of much longer duration. When Lyell began to write his book, he was well acquainted with a large part of western Europe, and had seen enough variety of environments and climates to realize how climatic factors condition the flora and fauna. In his travels to America, in the lower valleys of the Mississippi and the Ohio, he found a landscape that he correctly considered analogous to the forests and mangrove swamps of the Carboniferous, in which bituminous coal and lignite ('coal measures') were formed. This, however, led him to a conclusion that years later he would regret having written. He made the affirmation that, if the climatic conditions of the Secondary Era were repeated, the great reptiles that lived at this time could reappear on Earth (*Principles of Geology*, vol. 1, p. 123): "The huge iguanodon might reappear in the woods, and the ichthyosaur in the sea, while the pterodactyl might flight again through umbrageous groves of tree-ferns." Although he soon withdrew this affirmation from his writings, he found it hard to accept that throughout the history of life on Earth, substitutions and renovations of species of animals and plants had taken place. He did not fully accept this idea until long after his first meeting with Darwin. It took years of laborious dialogue and rigorous debate between the two scientists [11] before Lyell was finally convinced. In 1865, he began a profound revision of *Principles of Geology* and, in 1868, he published the tenth edition [24], in which he accepts the theories on evolution put forward by Darwin. This says much for the intellectual and human qualities of an already illustrious scholar who did not receive the recognition he deserved, possibly because many of his commentators have not had access to the later editions of his great work and limited themselves to analyzing the first edition, of which a facsimile has been published and is the most easily accessible.

5. Neo-uniformitarianism or neo-catastrophism?

Nowadays nobody argues against uniformitarianism as regards its significance in the uniformity of processes, but to accept that all those that have affected the Earth some time or another continue to act today is another matter [4]. In 1941, Lucien Cayeux [9] published a small but intelligent book entitled *Causes anciennes et causes actuelles en Géologie*, in which he affirms that despite the ''efficacy of the doctrine of present causes'', in the course of his research he came to the conclusion that ''*many ancient causes do not have an equivalent amongst present causes*.'' To support this affirmation, he presents cases of formations and sedimentary structures, which in his opinion could not be formed under the present conditions (phosphate deposits, oolitic iron minerals, chert nodules...): ''due to the cessation of a series of activities that have played a fundamental role in the formation of sediments throughout geological time'' while ''a characteristic of the ancient seas was the frequency of perturbations and the upsetting of the equilibrium inexistent in the present day'' as ''they do not manifest themselves in any place before our eyes.'' The answer is in this last phrase, as currently there are many processes which are happening on our planet but not ''*before the eyes*'' of anybody: the deeper parts of the Earth's crust, the depths of the oceans and many other places. Today, seventy years after the publication of the book of Lucien Cayeux, current processes have been discovered that explain practically all the examples he presented as being inexplicable.

Another difficulty in the interpretation of the materials in the light of uniformitarianism is the transformation they may undergo after sedimentation, that is to say metamorphism and weathering. The interpretation of metamorphic rocks as the transformation of sedimentary rocks was something anticipated by Hutton, but which was formulated clearly by Lyell. There was still an additional problem that both Lyell and Darwin perceived: the 'catastrophist' geologists interpreted unconformities of strongly folded beds overlain by practically horizontal ones as the result of a strong and brusque movement that affected the lower materials and ended abruptly, without affecting the upper layers. Lyell insisted that the apparent abruptness of the change of rhythm was the result of a break in the register, an interruption in the sedimentation that left no geological record for a certain lapse of time. The interruptions in the sedimentary register are completely accepted and demonstrated today; the time reflected in the sedimentary deposits is much shorter than that corresponding to the interruptions, as Darwin and Lyell had suggested. This does not mean that today it is not recognized that there have been times of acceleration and intensity of the processes. We know that in the history of the Earth, as in the history of Mankind, there have been times of calm and times of crisis. Crises that sometimes only affected a region, while others were global.

6. Ruptures of the equilibrium: the crises

Today geology, especially stratigraphy and historical geology, is at a very interesting and sometimes somewhat contradictory stage. When the scale of geological time was started, it was very convenient that experts in tectonics affirmed that orogenic movements did occur in folding phases, as described by Hans Stille [33]. If the phases had occurred synchronously across the planet, they could be used to delimit the ages and eras of the history of the Earth. So, in Europe the *Hercynian unconformity* could be used to separate the Palaeozoic from the Mesozoic. Later it was recognized that there was not a sole unconformity, but several ones, and the *Palatinian phase* and the *Saalian phase* were defined, the first between the Triassic and the Permian, the second one between the Upper and Lower Permian. In fact, a large part of Europe was subject to numerous tectonic pulsations that produced diverse intraPermian unconformities, heterochronous and of local or regional value. During this time, marine sedimentation continued in other parts of the Earth (southeastern China, Iran, Arctic...), and these series maintained the register of the 'lost moments'.

However, the 'old masters' were wise in placing these limits in areas and with methods that could later seem arbitrary. The limits fixed at the start between the great eras of the history of the Earth, Palaeozoic, Mesozoic, and Cenozoic, correspond in fact to important changes in this history. They were not always placed exactly but, as was guessed or intuited, corresponded to moments that in some respect represented the closing of one chapter and the opening of a new one. These changes were later detected in the fauna and flora, and today we know that they correspond to changes in the environment in which those ones lived, that is to say the climate, the composition of the atmosphere and the water of the oceans.

In the continuous marine series of the Upper Permian and Lower Triassic, one of the most important crises that had occurred in the history of the Earth and life since the ''Cambrian explosion'' has been registered. In a short period of time (in the geological timescale!), between 85 % and 95 % of living species disappeared and those characterizing the Mesozoic and the Cenozoic began to develop. This was at first thought to be the result of the impact of a great meteorite, but today it seems demonstrated that the principal causes were enormous volcanic emissions with extensive lava flows and the projection of large quantities of dust and toxic gases, which brought about modifications to the atmosphere and marine and continental waters as well as important changes in the climate [36]. Some call these events 'crises', others 'catastrophes', but we are really dealing with 'uniformitarian catastrophes'. The processes that caused them either continue to occur or may occur at any time in the future, and may be considered 'rare events', but certainly not 'mysterious' ones.

7. Actualism: theoretical geology and fieldwork

Accepting that the processes that originated the rocks and the structures of the Earth's crust are the same as those in action today brings us to a conclusion that Lyell was faithful to throughout his life. This is to consider that the only way to understand and explain the causes for the origin of the materials, structures, and forms of the Earth, in other words to practice geology and demonstrate his theories, is to observe and analyze the current geological processes: erosion, sedimentation, volcanic activity, etc., that is to say, do geological fieldwork. This is his main difference with Werner and Hutton and this is the main reason for which I say that Lyell is the first modern geologist.

From an early age, familiar tradition, intellectual curiosity and a love of nature drove Lyell to explore and make observations and analyses in the field. However, in 1827, when he decided to dedicate himself professionally to geology and write books to express his ideas, he arrived at the conclusion that he would have to extend his fieldwork to other countries and continents [35,39,40]. This forced him to rethink his future and he decided to leave the prestigious legal firm in which he worked and planned a long trip that would take him far from his native Scotland and the South of England, where he had lived for most of his life. From that moment on, Lyell's life centred on his travels and the preparation and writing of the book that would represent his life's work: *The Principles of Geology*. During his life, he travelled throughout all western Europe and the areas of North America that were accessible at that time. However, it was his first travels in France, Italy and Spain that had the greatest influence on the content of the first edition of his work, as he made these trips during the years in which he was preparing this edition.

8. His first travels to France and Italy (Figs. 2 and 3)

Before his historically more important travels to France and Italy, which Lyell made after deciding to dedicate himself exclusively to geology, he had already visited Paris, then the scientific capital of the world, partly due to the promotion of positive developments in the running of the University and other scientific institutions by Napoleon. In 1828, he spent two months enjoying the cultural and social life of Paris, attending conferences and gatherings on the subjects of geology, chemistry and zoology, and meeting some of the most

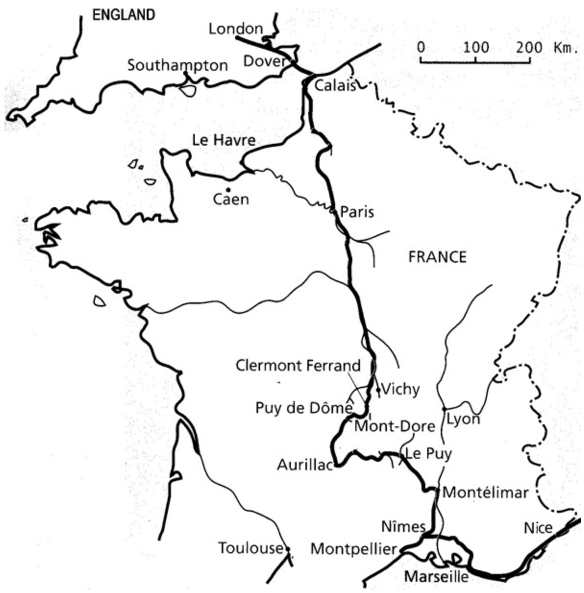


Fig. 2. Lyell and Murchison's tour in France, 1828 (from [39], modified).

Fig. 2. Voyage de Lyell et de Murchison en 1828, en France (d'après [39] modifié).

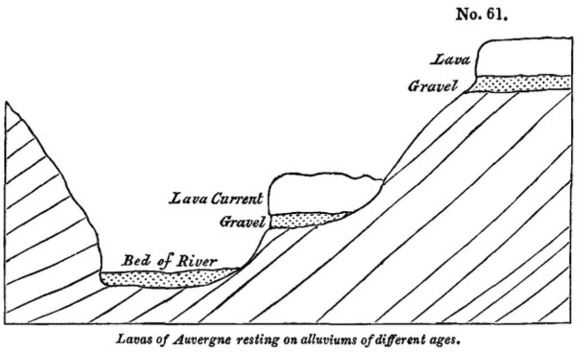


Fig. 3. Section of the current lavas and fluvial terraces in Auvergne (*Principles of Geology*, 1833, vol. III, fig. 61, p. 267) [21].

Fig. 3. Coupe dans les courants de lave et les terrasses fluviatiles d'Auvergne (*Principles of Geology*, 1833, vol. III, fig. 61, p. 267) [21].

important figures of the time. He met Brongniart and Humboldt and Cuvier's team, although he did not meet Cuvier himself, as he was not in Paris at this time [35,39] Figs. 2 and 3.

With Constant Prévost, he began his first scientific study: the Tertiary of the Paris Basin. Cuvier had started analyzing these formations a few years previously and was particularly impressed by the alternating nature of the levels, whose fauna and composition demonstrated that some had been deposited in a marine environment (fossiliferous limestone), while others had been deposited in a continental environment, principally lacustrine like the gypsums of Montmartre. He interpreted this as the result of a series of catastrophes that had produced repeated, sudden rising of sea levels, followed by equally violent elevations of the seabed, rising once again above the level of the ocean [10] (Figs. 4–8).

Fig. 4. Lyell's tour around Catalonia. The dotted line indicates uncertainty due to little information (from [2,39], modified).

Fig. 4. Voyage de Lyell à travers la Catalogne. La ligne en pointillés indique l'incertitude due au peu d'informations (d'après [2,39], modifié).

Constant Prévost discovered that marine and continental fauna appear together in the base layers of the Montmartre gypsums [28]. This demonstrated that they lived together at more or less the same time and therefore the changes could not have been so sudden or

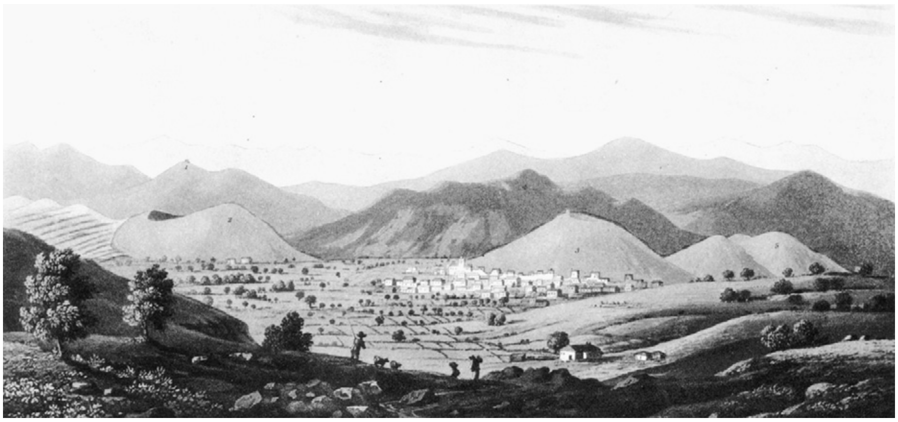
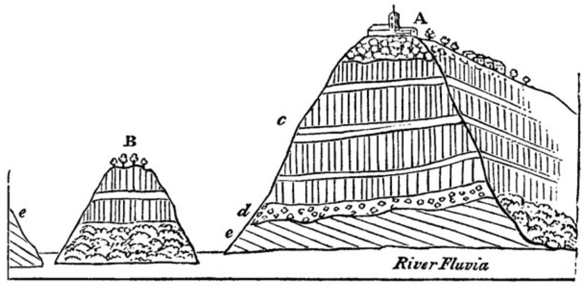


Fig. 5. The volcanoes of Olot. Frontispiece of vol. III of *Principles of Geology* [21].

Fig. 5. Les volcans d'Olot. Frontispice du tome III de *Principles of Geology* [21].

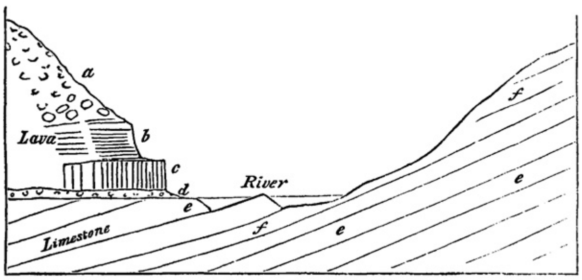


Section at Castell Follit.

Fig. 6. Section at Castellfollit, near Olot. **A**: Church and town on Castell Follit (sic.), overlooking precipices of basalt. **B**: Small island, on each side of which branches of the Teronel River flow to meet Fluvia. **C**: Precipice of basaltic lava, chiefly columnar. **D**: Ancient alluvium underlying the lava current. **E**: Inclined strata of secondary sandstone. (*Principles of Geology*, Vol. III, p. 190) [21].

Fig. 6. Coupe à Castellfollit, près d'Olot. **A** : Église et ville sur Castellfollit (sic.), surplombant les précipices de basalte. **B** : Petite île, sur chaque côté de laquelle coulent les affluents de la rivière Teronel pour rejoindre Fluvia. **C** : Précipice de lave basaltique, surtout columnaire. **D** : Ancienne formation alluvionnaire sous-jacente au courant de lave. **E** : Strates inclinées de grès secondaire. (*Principles of Geology*, Vol. III, p. 190) [21].

'catastrophic'. This idea had no chance of being accepted by the scientific community, as it was not in agreement with the theories of the great master: Cuvier. When Lyell studied these materials with Prévost, he undoubtedly remembered his observations of the British estuaries of the west coast and the interaction produced there between fluvial and marine waters. He confirmed the conclusions of his friend that it was not necessary to explain the successive stages of marine and continental sedimentation by the existence of 'ancient catastrophes'. Slight changes in sea level or in the barrier



Section above the bridge of Cellent.

Fig. 7. Section above the bridge of Cellent (sic.) near Olot. **a**: Scoriaceous lava; **b**: schistose basalt; **c**: columnar basalt; **d**: scoriae, vegetable soil and alluvium; **e**: nummulitic limestone; **f**: micaceous gray sandstone (*Principles of Geology*, Vol. III, p. 188) [21].

Fig. 7. Coupe au-dessus du pont de Cellent (sic) près d'Olot. **a** : Lave scoriacée ; **b** : basalte schisteux ; **d** : scories, terre végétale et alluvions ; **e** : calcaire nummulitique ; **f** : grès micacé gris (*Principles of Geology*, Vol. III, p. 188) [21].

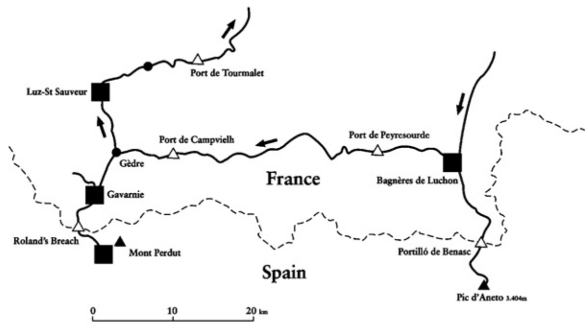


Fig. 8. Lyell and Cook's tour in the central Pyrenees, 1830 (from [3], modified).

Fig. 8. Voyage de Lyell et de Cook dans les Pyrénées centrales, en 1830 (d'après [3], modifié).

that limits the coastal lagoons, processes that are frequently in action now, are sufficient to explain the successive stages of marine and continental sedimentation. This affirmation was the starting point of the great contribution that Lyell made to the science of geology: *The principle of actualism*.

His following trip to France, during which he also visited Italy, was completely different, in both duration and approach. At the beginning of 1827, G.P. Scrope published a book [29] on the extinct volcanoes of central France, which deeply impressed Lyell, who subsequently wrote a review of the book for the magazine of the Geological Society. At this time, there was an important debate about the origin of lava and volcanic morphology. A French geologist, Nicolas Desmarest, had demonstrated in Auvergne, precisely in the centre of France, that the basalts were the result of the solidification of lava flows on cooling [12]. This idea was not accepted by many of the geologists of the day, who preferred the theory of Werner, the famous professor of Freiberg, which stated that basalt was the result of chemical precipitation in water. The debate between those who affirmed the aquatic origin of basalt, the 'Neptunians', and those who considered it to be of volcanic origin, the 'Vulcanians', went on for many years and Scrope's book revived this issue in Great Britain. On 10 May 1828, Lyell set off for Paris, accompanied by Murchison, on an expedition that lasted longer and was more fruitful than they had originally expected. They travelled around the French Massif Central, studying the ancient volcanoes and the relation between the basalt defiles and the valleys and fluvial terraces. This allowed them to confirm the volcanic origin of the basalt and their relatively recent age.

From Auvergne, they descended into the Rhone Valley, to study the Tertiary series that they wanted to compare with those of the Paris Basin. They arrived at the Côte d'Azur and, from Nice, made a long journey across the North of Italy, or more precisely, what would later be Italy after the unification of 1861. They visited Bologna, Padua, Florence, Siena, and Turin, where they stayed longer, as the Zoological Museum there had a large collection, which allowed them to compare the present-day fauna with that of the Tertiary of the Paris Basin, as well as of other regions of France and Italy. It was regarding the collections in the Museum of Turin that Lyell had the brilliant intuition that the Tertiary materials he had studied in different regions were not all the same age. In some places, the fossilized fauna was very different from present-day fauna, with very few species that are still living today, while in other places these species were much more abundant. After the fauna found in the Tertiary of different regions was studied by Deshayes, Lyell [21] decided that the fauna could be used as a criterion to define the age of the materials and divide them into three series: Eocene, Miocene, and Pliocene This was an important contribution to stratigraphic nomenclature, which is still valid today.

On his return to Nice, on 9 August, Lyell decided to continue his journey and went south, now without the company of Murchison. He wanted to compare the ancient volcanoes of Auvergne with volcanoes that were still active and the best place for this was the South of Italy. Beyond the Papal States, which at that time occupied most of the central region of the peninsula, stretched the Kingdom of the Two Sicilies, with Naples as its capital. It was a poor region, inhospitable and unsafe for travellers, but Lyell wanted to see and study the two most important volcanoes of the continent: Vesuvius and Etna. He was not only interested in the active volcanoes themselves, but also in their associated seismic movements; above all, he wanted to find out if these movements had produced deformations in the more recent deposits. He therefore took special interest in the coastal sediments. Amongst the many observations he made, one of the most important was on the island of Ischia, to the west of Naples. Here he found some clay and sandstone deposits that contained exactly the same fauna as that living today in the Mediterranean, confirming their contemporary age, despite being 200 m above sea level. At the Temple of Serapis near the town of Puzzuoli, next to Naples, proof that sea levels had varied in recent times was still more apparent. There remain only three columns of the ancient Roman temple, but an interesting history is inscribed on them. On the upper portions, the marble contains many perforations produced by the marine mollusc, *Lithodomus* (= rock dweller). The temple was obviously built on dry land, but the perforations caused by *Lithodomus* indicate that it was subsequently covered by the sea and later re-emerged when the sea level dropped. This was irrefutable proof that there had been an oscillation of the sea level of around 6 m since the construction of the temple, at the end of the first century AD, demonstrating that movements of the Earth's crust, and therefore its internal energy, continued to be active in recent times. Others before him had seen the history written on the columns of the Temple of Serapis, but Lyell knew how to relate it to the presence, also in this region, of marine levels well above the then current sea level, and therefore deduced that the Earth's internal energy had not run out.

Enthused by these findings, Lyell decided to cross the Messina Strait to visit Sicily and climb Etna. The deep valleys that cut the slopes allow the study of the internal structure of the volcano and the different layers of lava and other materials that form the volcano's cone, and which are interlayered with sedimentary material. He spent a few days in Syracuse visiting the museum, where he acquired a good collection of fossils. He then continued through the Centre and the North of Sicily, until he reached Palermo, where on 9 January he boarded a boat that took him to Naples, Rome, and Genoa, from where he finally reached Paris. Here he met up with his colleagues. He was especially anxious to discuss his new ideas about the Tertiary with Constant Prévost, and also with Cuvier, with whom he maintained a friendship despite their differences of opinion. On 24 February 1829, he returned to London. The scientific expedition had lasted nearly nine months, during which time he had covered more than 7000 km, an epic journey considering that there were neither cars nor railways. He had bought many books and fossils, and above all had filled many notebooks with observations and sketches. These notebooks contained the basis for his future book, whose first volume he began as soon as he arrived home.

9. Lyell's trips to Spain

Lyell first visited Spain in the summer of 1830 [1,2,32,35]. The first volume of the *Principles* had already been corrected, but he had not yet written the second and third volumes, which would contain many of the observations he made while in Spain. His main objective was to study the volcanic region of Olot, in Catalonia, and the region of the Pyrenees between Catalonia and Aragon. He was accompanied by his friend Captain Cook (1789–1856), lover of geology who knew Spain quite well and offered to act as a guide.

On 22 June, they left London for Dover and, having landed in Le Havre, they quickly crossed France, passing through Bordeaux and Toulouse. In Ax-les Thermes, they made their first observations on the Pyrenees, but at the border pass of Puigcerdà, they were confronted with so many problems with the Spanish border officials that Cook decided to abandon his trip to Spain and left for Bagnères-de-Luchon. Lyell continued his diplomatic negotiations in Perpignan and took advantage of the time spent waiting to make geological observations of the Tertiary sediments of the Cerdanya depression on the French side, and afterward he completed the study on the Spanish side. These were completely unknown and not included in the geologic maps of the time. He established their Miocene age and lacustrine origin by analogies with the sediments of the lakes of Scotland that he had previously studied. He published an article at the Geologic Society of London [22] about the Pyrenees, which was the first ever written by a British geologist on this subject.

When he finally obtained permission to enter Spain, he continued towards Barcelona via the border town of Perthus. He was not permitted to enter Spain with his horse, so he was forced to travel by stagecoach, which did not allow him to make any geological study during the journey. On his arrival in Barcelona, he visited the Captain General of Catalonia, the person from whom Lyell needed authorization for his trip. It was finally granted and Lyell set off for Olot and, during his journey, made interesting observations about the Tertiary of the Ebro Basin, the conglomerates of Montserrat, the blue shales of Vic, the evaporites in the salt mine of Cardona and the nummulitic limestones of Gerona, and recognized the lateral change from continental to marine facies. All of which he meticulously recorded in his field study notebooks [2,37].

On 27 July he arrived in Olot [1,32], where he was warmly welcomed by the pharmacist, Francesc Bolòs, who had already studied the volcanoes with Pourret [27] and published two studies about them [6,7]. Bolòs accompanied Lyell on his route through the volcanic region. His interest for this region was related to his theory of the Pliocene age of these eruptions, intermediate between those of the French Central Massif (which he considered Miocene) and ones still active in southern Italy (Etna and Vesuvius). The observations carried out there were recorded in his notebooks and included in the third volume of the *Principles*. He drew some excellent panoramas of the city of Olot surrounded by its volcanoes, which would later be used for the frontispiece of this third volume. This was the first detailed study of the volcanic region of Olot, and had a wide dissemination, although the region had previously been cited by Bowles [8], Pourret [27], Maclure [25], and Bolòs [6].

Having finished his studies, he left for the border pass at Ceret, where once again he was confronted with problems, not only with the customs but also because of disturbances that had broken out in France at the end of the reign of Charles X. Finally, on 16 August, he met up again with his friend Captain Cook, who was waiting for him in Bagnères-de-Luchon, and they began to prepare for their exploration of the Pyrenees [3]. They wished to complete two north–south sections of the outermost eastern and western central Pyrenees. Immediately after Luchon, they travelled towards Portillo de Benasc and the Aneto Massif. Afterwards, on the French side of the Pyrenees, they continued west and from Gèdre they completed another section of the range from Gavarnie to ''Mont Perdu and Orlando's Breach'' (sic). In his notebook, he reproduced several interesting geological sketches of the region and demonstrated that in the formation of the mountain range, several orogenic movements of different ages had intervened, some of which having taken place long after the Cretaceous. Élie de Beaumont had just finished an article this same year [13] following the catastrophic theories of Cuvier and arguing that the European mountain range had been created in short and intense periods of orogenic movements. He supposed that the Pyrenees had been created in the *Cretaceous revolution* ''d'un seul jet''. Obviously, Lyell could not agree with these *revolutions*. He thought that orogeny was produced over very long periods of time as a result of several different pulsations, and he knew that the study of the structures and of series of strata could demonstrate this. Lyell did not publish any article on this issue, but his observations are conserved in his field notebooks (Kinnordy archive) and his conclusions are gathered together in the third volume of the *Principles*.

The exploration of the Pyrenees ended at the Basque coastline in Bayonne, where the cliffs of the littoral allowed them to observe the flysch. Lyell's attention was drawn to the monotonous repetition of the layers of sandstone and clay, but he did not manage to interpret their origin correctly. However, he made some accurate reflections on the nature of the sedimentary structures, which he drew and included in his book. Once the trip had finished, Lyell went on to Bordeaux and then to Paris, where he arrived on 27 September 1830. Once in Paris, he met again with Deshayes, and together they examined the fossils that Lyell had brought back from his trip, and prepared the palaeontological study of the Tertiary materials.

For Lyell, these trips and the fieldwork he carried out on them confirmed his theories. He knew that the Earth's history was not contained in any book, but in the rock layers that form its crust, in its structures, and its fossils. Written in a language that can only be understood through the knowledge and analysis of the geological processes that can be observed in the present. For this reason, he commented that his book *Principles of Geology* is "an attempt to explain the former changes of the Earth's surface by reference to causes now in operation".

10. Conclusions

It is evident that Lyell had a different vision of the constitution and history of the Earth from that we currently have due to recent discoveries and new working techniques, but he clearly left us with concepts that are still valid.

To accept the uniformity of the geological laws and processes does not mean to say that their intensity has always been the same or that they have always "worked" in the same way. Weathering and soil formation follow the same physical and chemical laws both in equatorial and arid regions, but the results are very different between the case of virgin jungle and that of the desert. Similarly, throughout the history of the Earth, the distribution of the continents and oceans, the duration of the days and years, the composition of the atmosphere and seas, orogenic activity and the received solar energy have varied greatly, but this does not stop us from being able to apply the principle of actualism as formulated and reformulated by Lyell throughout his work.

Lyell does not deny that, at certain moments, exceptional episodes are produced, which interfere with the 'normal course' of the more habitual processes. Now these are called 'rare events' and are defined as 'unlikely or rare events' that require 10,000 million years to have a 95 % probability of occurring at least once. They could be of terrestrial origin, such as intense and extensive volcanic eruptions, or extraterrestrial, such as brusque and important changes in solar radiation or impacts from meteorites or asteroids. None of these processes either breaks the uniformity of the laws of nature or escapes geological analysis, although they profoundly disturb the dynamics of the Earth. Perhaps the most important teaching of Lyell is that scientific research in Geology should not accept the existence of 'ancient causes', or processes and phenomena of the past without having a proof that demonstrates their actual existence. Any formulation of theory should be contrasted with reality, and when data obtained from observation or experimentation do not 'fit in' with the theory, the theory should be abandoned or reformulated rather than trying to 'force' the facts so that they adapt to the theory.

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