The Scientific Revolution of the 17th Century

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With the formation of a new Protestant court in England under James I, it was there that a great revolution in science took hold and began to flourish. Led by Francis Bacon (1561–1626), an administrator in the court of Elizabeth and then James I, his vigorous denunciation of the dead hand of the medieval past which had fostered such beliefs that a purposive nature had created material changes in corals and marine fossils through an innate mystical force of "stone-forming essences" began the complete revision of knowledge.

The main problem natural historians faced was that throughout the medieval millennium, many of the classical Greek manuscripts had either disappeared or been destroyed by zealous Christians intent on obliterating pagan culture. Fortunately, Aristotle's surviving writings, like so much of the *corpus classicum*, had become transmitted in Latin translations, many in Arabic versions in the era of Muslim high civilization, 8th to 13th centuries, and then retranslated into Latin and finally back to Greek, although often in faulty versions by barely literate scribes in the monastic scriptoria. Probably the most extreme example was the fate of *De plantis* which went from Greek to Latin to Arabic, then back to Latin by an incompetent translator, and finally again to Greek. To this day, we have only a limited idea of exactly what Aristotle wrote or actually intended in his study "On Plants".

Bacon was intolerant of the continued acceptance of debased Aristotelian teachings that had been transmitted uncritically for nearly two thousand years. "The entire fabric of human reason", he began in the *Prooemium* to his outline sketch in the "Great Instauration", a manifesto for reform, "is badly put together and built up, like some magnificent structure without any foundation". It was essential, he wrote, "to try the whole thing anew on a better plan, and to commence a total reconstruction of sciences, arts, and all human knowledge, raised upon the proper foundations". In 1605, he published the first part of that project under the title "The Advancement of Learning".

All knowledge, he argued, comes primarily from experience of the sensible external world, echoing a fundamental Aristotelian doctrine. To that time, Christianity had been mainly influenced by the Neoplatonic view propounded by St Augustine in the 5th century that all human knowledge begins with divine illumination of ideas implanted by God. By the 12th century, however, in the furious debates that raged in the early foundation years of medieval universities, the Dominican monk Thomas Aquinas created an ecclesiastical frenzy with his assertion, following Aristotle, that despite the creation of the world by an omnipotent God, nothing exists in the mind that had not come first through the senses: *nihil est in intellectu quod non prius fuerit in sensu*.[1] So incensed was the Catholic Church that on his death, Aquinas was buried in unconsecrated ground, although 50 years later in 1323 after the debates of the Scholastic Controversy had been resolved and his views became acceptable, he was rehabilitated. Miracles were attributed to him; he was canonized as St Thomas and named one of the great foundation fathers of the Church.

Following that Thomist precedent, Bacon continued his pressure for reform in 1620 with the publication of further stringent criticisms of existing natural history in *De augmentatis scientiarum* (The Enrichment of Knowledge). His revolutionary proposal was to replace the corrupted tradition that relied heavily on dialectical reasoning rather than field study, with his new instrument for achieving certainty, *Novum Organum*, which he set out clearly in the subtitle as "True Directions concerning the Interpretation of Nature". A fresh start was urgent, a renovation of all existing knowledge, and he advocated new methods of intensive observation, experiment, and the careful, wide-scale collection of data. In his various works, the doctrine of inductive scientific method, later called empiricism (Gk *empeiria*, "experience"), was introduced which codified a methodology of investigation that began to challenge a 2000-year tradition of reliance on authority.

After Bacon's dramatic declaration in 1605 to discard the "false idols" of the past and to begin a complete renovation of knowledge, two complementary themes of reef investigation

[1] Aquinas: *Quaestiones disputatae, De veritate*, q. 2, argument 19.

J. Bowen, *The Coral Reef Era: From Discovery to Decline*, Humanity and the Sea,
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emerged as the revolution gathered pace. Initially, how were the necessary geological structures formed that allow corals to become established? Then, following closely, what exactly are the biological processes underlying the development of what is essentially a veneer of living organisms—plant and animal—that collectively build the ecosystems known as coral reefs? The biological quest soon became as equally absorbing a scientific pursuit as the geological problem. The history of coral science, in fact, has proceeded in a fascinating counterpoint as the two issues interacted, each discovery casting light on the other.

At that time too, a new concept also began to appear when science (from the present participle stem of the Latin *scire*, "to know") began to replace natural history, with a totally different emphasis. Bacon continued to use the term "natural history", although he regarded it as the preliminary stage of collecting facts and recording the events themselves: he reserved the term "science" for the more probing, experimental investigation of nature. Bacon's call for a renovation of knowledge, despite church condemnation, continued to spread, and it began to be pursued with the increasing foundation of learned societies. The lead had already been taken in 1601 when, under the patronage of Prince Federigo Cesi in Rome with the support of the humanist scholar Nicolas-Claude Fabri de Peiresc and scientist Galileo Galilei, a group formed Europe's first scientific society which met under the name Accademia dei Lincei, literally "Academy of the Lynx-Eyed". With the name suggesting a penetrating observation of nature, it made some of the first uses of the microscope, possibly devised by Galileo based on his invention of the telescope, and in 1625, the Academy published a study of the honeybee, the world's first microscopic report, in its Proceedings, *Gesta Lynceorum*.[2]

New vistas of the universe that had been initiated in the Renaissance from the astronomical work of Copernicus and Galileo, and the incredibly dynamic impact of Bacon's uncompromising manifesto began to stimulate scientific enquiry continent-wide that was extended rapidly by the new medium of the printing press. Scholars across Europe came together to form radically different investigation societies, and their reports of experiments and investigations multiplied and were disseminated ever more rapidly. Reef science in particular was swept up in those new developments.

Two particular centres in Paris became major distribution outlets for publications, founded sometime around 1610 when two brothers, Pierre and Jacques Dupuy, formed a small group to meet in their home, which evolved into the Cabinet des Frères Dupuy, significantly, with a portrait of Francis Bacon the centrepiece. The other was in the cell of the Minimist friar Marin Mersenne in the Couvent de l'Annonciade in Paris, and it was to those early editors that papers were sent and disseminated throughout Western Europe in the early decades of the scientific revolution (Bowen (1981, III: p. 46 f.).

In 1630, a similar society was founded in Florence under the patronage of the Medici which called itself the Accademia del Cimento (Academy of Experimentation), with the motto *Provando et riprovando* (Test and test again), their proceedings being published in the *Saggi di naturali Esperienze* (Reports of Experiments in Natural History). Then, in 1633, came the papal condemnation and house arrest of Galileo for his heretical claim that the earth revolved around the sun. The repressive hand of the Inquisition, which monitored all scientific investigation closely, forced the closure of the scientific societies in Italy, confirming the popular jest of the time that Italy could lead the world in science whenever the Inquisition would let it.

Of the large number of scientific societies that appeared in the mid- to late 17th century, three became pre-eminent, all in operation to the present day. The first was the Collegium Naturae Curiosorum (Society for the Investigation of Nature), founded in 1652 by a group of physicians in the German city of Schweinfurt, some 115 km east of Frankfurt, followed by the Royal Society of London, founded in 1660 and chartered by Charles II in 1662, quite explicitly, on Baconian principles. The third, a French equivalent, arose slightly later, founded by Chief Minister Colbert in 1666 as the Acadèmie des Sciences, which built upon the work of earlier French societies. Through those organizations, and others that followed in Denmark, Holland and Italy in particular, the new spirit of Baconian-inductive empiricism became dominant, and it was the consequent burst of activity on so many fronts that gathered momentum and created an ever-growing ferment of ideas in natural history.

Following the foundation of those societies, a number of journals soon appeared, originally independently financed, expressly designed to disseminate the increasing volume of scientific findings. The first came in January 1665 when Denis de Sallo of the French parliament founded the *Journal des Sçavans*, followed in March the same year in London by the *Philosophical Transactions;* Italian, Danish, Dutch and German journals then appeared between 1668 and 1682. In the late 18th century, the *Philosophical Transactions* became formally linked to the Royal Society of London, and in 1903 the *Journal des Sçavans* received official government sponsorship under the Institut de France.

New Directions: Earth Processes and Natural Causes

Meantime, throughout the 16th and 17th centuries, as mining progressed and men dug more deeply into the surface of the earth, marine remains, now termed fossils (Lat. *fossilis*, from

[2] Italian, *gesta:* deeds, achievements (of the lynx-eyed).

fodere, to dig) continued to be found in increasing numbers, as Fracastoro had observed, scattered throughout the layers of unconsolidated earth being excavated. That raised two related issues: How had the visible layers of the earth been formed within which marine fossils were being found, and how had the landscape been shaped?

That is when we find the beginnings of a theory of stratification of the earth's surface set out by Niels Stensen (1638–1687) of Denmark in his 1669 study with the opaque title *De solido intra solidum naturaliter contento dissertatio prodromus* (perhaps best translated as "A theory of the interaction of natural pressures within the solid earth") in which he attributed the energizing force to volcanic activity. Volcanoes, clearly related to the natural pressures operating within the earth, were particularly threatening phenomena, carrying a mass of superstition. The first major historical account is in the *Timaeus* by Plato, c. 340 BC. In a battle between Athenians and Atlanteans, the conflict ended abruptly during a period of violent earthquakes and floods when, in a single horrendous day and night, all the warriors were swallowed up by the earth, and the island of Atlantis similarly disappeared beneath the sea: *e te Atlantis nesos osautos kata tes thalattes dusa efanisthe*.[3] That legend, believed to have been based on the destruction of the Minoan civilization on Crete as a result of the volcanic explosion of the nearby island of Santorini, perhaps around 1500 BC, became a central feature of all volcanic knowledge thereafter.

Accounts recorded subsequently were historically accurate. Several have become folklore: the explosion of Vesuvius in 79 AD, in which Pliny died from asphyxiation aboard his yacht in the Bay of Naples in a foolhardy endeavour to observe its activity at close range; and the subsequent eruption of Etna on the eastern coast of Sicily in 353. The eruption of Hekla in Iceland in 1104 received powerful religious sanction when it was authoritatively declared by the resident Benedictine monks that its fiery crater was the portal to Hell itself. As the New World became progressively explored, so accounts came in from the Caribbean Antilles, the Dutch East Indies and the Pacific Ocean. By 1650, Varenius, considered to be the founder of modern geography, published a list of the then 27 known volcanoes in his great treatise, *Geographia generalis*.

To explain the entrapped marine remains, Nicolas Steno, as Niels Stensen was known in the latinized form of his Danish name, argued that, in the course of time, the earth had been covered by water-borne sediments that formed layers of sedimentary beds, although, when the first layer was formed, "none of the upper Beds was extant". Owing to continued subterranean water erosion and disturbance from volcanoes and "underground fire", he continued, the superimposed strata eventually gave way and became "either perpendicular to the Horizon, or inclined to it", and "such changed situation of the beds is the chief cause of mountains". Steno had made a significant linkage between fossils and rock strata, and the natural forces of erosion that shape surface topography. One of his most tantalizing comments, which hinted at continuing surface movements, was the statement that "All mountains at this day have not existed from the beginning of things" (Stensen 1669, p. 28). Unfortunately for Steno, those views clearly contradicted Biblical dogma, and so great was the pressure from the Evangelical Lutheran bishops of Copenhagen that he was forced to abandon further geological speculation.

The deposition of sediments containing fossils and the stratification of the earth was a puzzle also examined critically in Protestant England by Robert Hooke, Curator of Experiments for the Royal Society in 1662 and thereafter Gresham Professor of Geometry. A controversial scientist of equal stature and achievements as his adversary Isaac Newton, he published *Micrographia*, a pioneering work describing his investigations into minute life, in 1665. Presented in English instead of the customary Latin, it is a compendium of 60 separate Observations on a wide range of subjects, from ants to writing. Each observation, most of several pages, with the majority on living organisms, generally covered a number of related issues, into which Hooke inserted his conviction that most of the daily operations of the world proceed according to natural laws. Following the same line of reasoning as Steno, after a short vacation to his childhood region on the Isle of Wight, Hooke recorded his exploration of the sedimentary strata of the cliffs. On one occasion, he recollected, from a "Layer, as I may call it, or a Vein of Shells…I digg'd out, and examin'd many hundreds and found them to be perfect Shells of Cockles, Periwinkles, Muscles, and divers sorts of small Shell-Fishes…some perfectly intire". What also captured his imagination was the composition of the rock face itself which, he reasoned, had originally been composed of suspended earthy particles and "in tract of time had settled and congealed into…hard, fixt, solid and permanent forms" (Hooke 1665, p. 176).

From his investigation of elevated strata and temperamentally driven by his inner demon—often to the irritation of his colleagues and senior fellows of the Royal Society—Hooke dismissed the sports of nature as absurd myths. In particular, in one of his most extensive and critically analytical descriptions in Observation XVII of *Micrographia*, "Of Petrify'd wood, and other Petrify'd bodies", dealing specifically with frequently found fossilized sports of nature, he totally rejected Augustine's belief in stone-forming essences (Hooke 1665, pp. 107–112). On the contrary, he argued, they were the empty shells of once living animals—"*Nautili* or Porcelane shells;…shells of *Cockles, Muscles, Periwinkles, Scolops*, &c. of various sorts"—which "came to be thrown to that place… by some Deluge, Inundation, Earthquake…

[3] *Timaeus* 25 D.

there to be fill'd with some kind of Mudd or Clay, or *petrifying* Water" and not by means of "some extraordinary *Plastick virtue latent* in the Earth itself" (Hooke 1665, p. 110). Petrified marine objects, he argued, were comparable with the remains found in classical civilizations, declaring that "shells are the medals, urns, or monuments of nature…discoverable to any unbiased person" that would afford more information about the past than "all the pyramids, obelisks, mummies, hieroglyphs and coins provide to archaeologists". The only limitation, he added, was that in the present state of knowledge "it is very difficult to read them, and to raise a *Chronology* out of them, and to state the intervals of the times wherein such catastrophies and mutations have happened".[4]

Hooke's investigations with the microscope led him to speculate at the same time on the broad geological features of the earth, particularly the action of volcanoes, earthquakes and other surface movements of the crust. Over a 30-year period, he developed those ideas into a series of lectures and discourses for the Royal Society, mainly in the two years 1668 and 1669, and which, following his death in 1703, were collected and edited by Richard Waller and published in 1705 by the Royal Society under the title *Lectures and Discourses of Earthquakes and Subterranean Eruptions*.

Hooke's "Discourses" were equally controversial. Earthquakes and volcanic action, he argued, were not events expressing some mysterious divine wrath, with the lava foreboding the fury of Hell, but a major natural phenomenon resulting from the spontaneous combustion of sulphur, pyrite (iron sulphide, FeS_2), air and salt water—because most volcanoes then known were either in the sea or along coastlines—which subsequently created uplift and modelled the landscape. His approach consequently marks one of the most significant changes in our understanding of the formation of coral reefs, when the speculations of earlier naturalists were consolidated into a firm theory that paved the way for systematic, rational scientific investigation. Just as he had explained the petrification process in fossils, so Hooke proposed the manner by which sedimentary strata became consolidated, and that "every part hath, at some time or other, been shaken, overturned, or some way subject to earthquakes, and been transformed by them. It seems to me", he argued, "very absurd to conclude, that from the beginning things have continued in the same state that we now find them" (Hooke 1705, p. 450). Those conclusions were a remarkable advance in geological thinking.

Perhaps even greater evidence of Hooke's inductive genius was the observation that many of the fossils being unearthed in England were also coming from tropical regions: perhaps other scientists, he suggested, would consider that "this very land of England…did at a certain time for some ages past, lie within the torrid zone".[5] Equally indicative was his anticipation of some kind of evolutionary mechanism directing animal life. From available evidence, he argued that because there were "many other species of creatures in former ages, of which we can find none at present…'tis not unlikely also that there may be divers new kinds now, which have not been from the beginning". Moreover, it cannot "be doubted but that alterations of this nature may cause a great change in the shape, and other accidents of an animated body" (Hooke 1705, pp. 342–343, 435). With the thoughts of Steno and Hooke, which brought together the concepts of sedimentation, fossil entrapment and the activity of surface water and volcanoes, the groundwork for the emerging science of geology was created.

Even more evidence came in 1707, just two years after the publication of Hooke's discourses on earthquakes, when Europe was astonished by the incredible news of the eruption of the Mediterranean island of Nea Kameni from the legendary volcanic caldera of Santorini, in many minds confirming the legend in *Timaeus*. Reasoning from that event, and from his investigations in the Italian mountains, in 1740 the Carmelite priest Anton-Lazzaro Moro published *De Crostacei degli altri marini corpi che si truovano su' monti* (Crustacea and other marine bodies found in mountains). Despite his vocation, he supported the views of Steno and Hooke that volcanoes were the active agents in shaping the landscape, and that eruptions trigger uplift of the surrounding terrain, thereby accounting for elevated marine strata.

A Flowering of the Intellect: The European Enlightenment

The intellectual temper of northern Europe was rapidly moving into a new phase. The manifesto of Francis Bacon in 1620—*De augmentatis scientiarum*—for a repudiation of the heavy hand of medieval tradition and in its place a complete renovation of knowledge, along with the formation of scientific societies, despite their closure in Italy by the Inquisition, marked the beginning of a new spirit of scientific enquiry. Although the authority of the various religious confessions was still intimidating, demanding belief in a universe constantly under the direct guidance of a transcendent God—a doctrine known as Theism—thereby encouraging supplication during volcanic eruptions and other catastrophes for miraculous intervention, scientific thought was beginning, nonetheless, to take firm hold. Initiated in large part by the quest to solve the coral reef enigma, it had begun to exercise a pervasive influence, particularly evident in the growing acceptance of earthly processes as resulting from natural causes.

[4] Hooke (1705, pp. 335, 431). Published posthumously two years after his death in 1703.

[5] Current geological knowledge places England at 35°N in the Triassic period, c. 251–206 million years ago (Mya).

A defiant stand was taken in 1687 when Isaac Newton (1642–1727) presented his wide range of investigations in one of the most influential books yet published, *Philosophiae naturalis principia mathematica* (Mathematical principles underlying nature). Although it drew from the ancient philosophies of Pythagoras and Plato by asserting that the universe originated from a divine mathematical design, once created, he argued, its daily operations follow fundamental physical and mechanical laws. With the powerful stimulus of Newton's *Principia* asserting the primacy of natural processes, and an increasingly frequent denial by philosophers of the direct activity of God in daily events, scientific thought came to reflect an alternative, rational approach known as Deism. A neologism created in 1678 by Ralph Cudworth, Deism was developed extensively by John Toland (1670–1722), an Irish convert to Protestantism, who attempted to relate the evidence of natural history and scientific discovery to issues of faith. Strongly influenced by the "Ethics" of Benedict Spinoza of 1670 in which God and nature were presented as an entity, expressed in the intriguing double entendre *Deus sive natura* (God is Nature, and Nature is God)[6] to describe that new conception, Toland introduced a new term into the religious lexicon to define that indissoluble unity: Pantheism. Toland's numerous writings initiated a great wave of radical thought that swept throughout northern Europe, Britain and the American colonies for the following century and began the movement known as Natural Theology, which became especially popular in England.

The Deist position was argued even more forcefully by John Locke (1622–1704) in his challenging *Essay Concerning Human Understanding*, c. 1690, where he rejected the conventional theological view of St Augustine, derived originally from Plato and steadfastly maintained down through the centuries, that our ability to reason and reach valid knowledge depends on ideas implanted by God at birth (*a priori*). Adopting a more radical position than Aquinas and presenting it in a school-room metaphor, Locke asserted that at birth the mind is a blank tablet (*tabula rasa*) and that all human knowledge is written on it throughout life by experience (*a posteriori*). Then, going further, in his 1695 treatise *Reasonableness of Christianity*, he also argued that earthly operations occur solely according to natural laws. Science, for Locke, had to be based entirely on human observation and reasoning inductively from data obtained empirically. Even more radically, he wrote, from that viewpoint it becomes impossible even to speak of divine processes because they are, by definition, beyond empirical confirmation. Committed believers, in significant contrast, were compelled to remain subject to the coercive power of ecclesiastical institutions, especially in Catholic countries where the Congregation for the Doctrine of Faith, the dreaded "Hammer of Heretics" (*Malleus malefactorum*) founded around 1230 and known generally as the Inquisition, continued to be repressive.

Deism developed ever more strongly as the 18th century progressed, and it rapidly spread to France where demands for freedom from ecclesiastical authority and for independence of thought were stimulated by the writings of Voltaire, Rousseau and the *Encyclopédistes*, in particular those by Denis Diderot and the political philosopher Montesquieu. Believing themselves to be particularly enlightened, their writings began the intellectual movement of the Enlightenment, known in France as *l'Éclairissement*, and in Germany as *die Aufklärung*, where Christian Wolff and Immanuel Kant were the major influences.

In Britain, some of the greatest British radical thinkers achieved equal prominence, including economists Adam Smith and Jeremy Bentham, historian Edward Gibbon and scientist Joseph Priestly. It was in Edinburgh, in particular, then Europe's leading intellectual centre, and known as "Athens of the North", where it burgeoned into a brilliant flowering of the intellect. During the aptly named "Scottish Enlightenment", its greatest luminary, David Hume (1711–1776), achieved fame for a number of highly provocative, challenging philosophical works, continuing the pattern created by Locke.

Considered by many the finest philosopher ever to write in English, the leading thrust of Hume's thought was to reject all metaphysical constructions, and to assert the principle of skepticism as the fundamental framework within which scientific inquiry must proceed, based on reasoning solely from observable, natural causes (Hume 1748). Direct knowledge of God, the *via negativa* or apophatic approach of mystics, Hume asserted, is "altogether incomprehensible and unknown to us": our idea of God can only come from observation of "effects that resemble each other" created by the "Author of Nature". Only "by this argument *a posteriori*, and by this argument alone", he asserted, "do we prove the existence of a Deity" (Hume 1779, pp. 700–701). Even causes as such were rejected by Hume who pointed out that causes can never be observed: they are inferences drawn from analysis of a sequence of events. Although he accepted an original Author of Nature, in his view science was the patient investigation of phenomena, gained solely from a multitude of observations through our senses, and the inferences drawn by the association of ideas and valid logical reasoning. Such inferences, he asserted, constitute the totality of all human knowledge. Even more significant was Hume's assertion that nothing is ever completely predictable because so-called scientific truths are constantly overturned as new discoveries, based on observations, continue to be made.

The philosophical position of Hume marked a turning point where Theism and the belief that all creation came according to a Divine Design were becoming forced into apologetic and defensive responses. Henceforth, neither

6 Literally, God or Nature.

the Inquisition nor the bishops of Copenhagen could direct scientific inquiry along theological channels: geology was to become uncompromisingly Newtonian in approach and many scientists began to use only physical and material concepts to report their discoveries, which became apparent in the continuing geological quest to understand the origin and formation of coral reefs. The impact on subsequent scientific endeavour was to be enormous, e.g. the puzzle of explaining the origin of the extensive relict coral reefs in the French Jura Mountains.

Rational Science and Earthly Operations: Neptunists and Plutonists

Throughout those years of the scientific revolution, the geological issues raised by Steno and Hooke continued unabated, and they reached a climactic phase with the conflict between conservative professors of mining practices and scientists attempting to understand earth processes as natural phenomena. The quest of the empirical scientists was to establish a valid body of evidence to challenge the traditional belief that the rocky earth had developed from precipitation of chemicals within the primeval waters of Divine Creation and in some mysterious way had assumed its modern appearance.

Mining professors were naturally resistant to emerging ideas: their craft had a venerable history reaching back to the Bronze Age 5000 years earlier when ores were first mined, smelted and fashioned into an increasing range of artefacts. As the earth is composed mainly of inorganic crystalline chemical elements and compounds, collectively termed minerals, within which reside a smaller range of elements and compounds with workable qualities of malleability and ductility, known as metals, the mining quest was to discover those places with sufficient concentrations of metallic ores to justify economic extraction. By the time of Agricola in the 16th century, when he presented a remarkable scheme of classification of metals in his 1545 treatise *De re metallica*, along, as mentioned previously, with a short section on corals, mining had become a highly developed occupation with a considerable body of practical knowledge. By the 18th century, schools of mines in Europe, particularly in Germany and Hungary, had become well established, and their approach was to enable students to identify various strata based on qualitative criteria of mineral and metal content, now even more important for the increasing needs of industry as the new machine-based technological era was beginning.

Strong leadership for the conventional miners began in 1775 when, at the age of 26, Abraham Gottlob Werner (1749–1817) was appointed Director of the Freiberg School of Mines. Holding that position for 40 years, he developed a theory of earth formation that eclipsed all others and drew a succession of students from all over Europe, so coming to influence an entire generation. Werner was controversial from the start with his firm belief in the Biblical theory of the original formation of the earth from water, and the ensuing 40-day deluge. In his day, there was no technology for investigating the physical processes within the interior of the earth or for estimating its age; chemistry was still in its early formative stages, crystallography was not to become a science until after the 1850s. How the hard rocks had been formed remained a mystery, but Werner, himself a Deist, was dogmatic in his assertion they had been precipitated from dissolved minerals within the primeval fluid at Creation and subsequently shaped by catastrophes and inundations, from which softer strata had then been weathered.

Unfortunately for the historical record, Werner wrote just two short books, and most of his theory, which he named Geognosy (Gk *geo*, "earth" + *gnosis*, "knowledge"), was generated around Freiberg in the central European regions of Saxony, Hesse, Bohemia and the Erzgebirge (literally, ore-bearing ranges), then the greatest mining region in Europe. Apart from his brief and highly regarded *Von den ässerlichen Kennzeichen der Fossilien* (On the exterior characteristics of fossils), his only work on mineralogy was the *Kurze Klassification und Beschreibung der verschiedenen gebirgsarten* (Short classification and description of various types of mountains) of 1787, in which he classified strata according to their mineral content. In those works, Werner taught that the interior of the earth is cold and that volcanoes are caused by the underground combustion of coal; they are, in effect, mere epiphenomena on the earth's crust that make no significant contribution to its structure and had not existed at the time of original creation.

Beginnings of Dissent: The Influence of Volcanoes

Werner's teachings, however, became increasingly challenged as a considerable body of evidence became coordinated into an alternative theory of earth formation, centring on the role of volcanoes, and expressing doubt that basalt, granite and similar hard rocks had been consolidated from underwater precipitation. Werner, though, had generalized from his limited field experience in Saxony and adjacent Hesse, where all of the accessible basalt lay in elevated strata on the top of hills. Beyond, in the valleys of the appropriately named Massif Central in the French Auvergne, lay the great basaltic formations of the Chaîne des Puys (Chain of Peaks) west of Clermont-Ferrand, of which he had no knowledge. Several decades earlier in 1752, in a *Mémoire* to the Académie Royale des Sciences, entitled *Sur quelques Montagnes de France qui ont été volcani*, Jean Etienne Guettard reported that his study of a number of former volcanoes in France revealed they had been formed by subterranean activity.

Basaltic rocks were central to the entire issue of geology then. One of the most abundant minerals on earth, the growing controversy and heated conflict with Werner arose from the latter's insistence that basalt, the hardest rock on the planet—first named "basalts" by Pliny from the Greek *basanos*, the touchstone against which gold and silver could be tested for purity by their streak, and known popularly as "whinstone"—came from precipitation in the primeval waters of Creation. Yet its chemical composition, dominated by iron, manganese and calcium, from the tests available at the time and confirmed by numerous observations, gave clear indication that it had been formed by fusion at great heat. In search of evidence, for nearly 30 years, between 1766 and 1794, the British ambassador to the Court of Naples, Sir William Hamilton, an enthusiastic student of volcanoes, had made more than 60 expeditions up Vesuvius to observe it erupting and to collect specimens. In the same period, in 1771 Nicolaus Desmaret continued investigations into the Chaîne des Puys and from his observations, and the collections of lava made by Hamilton at Vesuvius, established that basalt and lava are the same mineral: he reported it as so in his *Mémoire sur l'Origine et la nature du basalte à grandes colonnes polygones* (Memoir on the nature and origin of the great basalt columns).

Providing further confirmation were the findings of Peter Pallas (1741–1811), a German in the service of Catherine the Great in the Academy of St Petersburg whose research, in both Europe and Russia, came to advance coral reef studies considerably. In his major work published in Paris in 1782, *Observations sur la formation des montagnes, et les changemens arrivés à notre globe* (Observations on the formation of mountains and the changes effected in the world), he invoked both fire and water as the forces of change, writing that "The operations of volcanoes have continued in different places, especially in the vicinity and at the bottom of the seas up to our own day. It is by their agency that new islands have been seen to rise from the depths of the ocean; it is probably they which raised all those enormous calcareous Alps, formerly coral rocks and beds of shells, such as are still found today in the seas which foster these productions" (Pallas 1782, p. 76). Of great significance in that statement of Pallas is the comment "up to our own day", a theme that rests implicitly in all investigations into the formation of strata. Despite the attempted forcing of science into a restrictive theological mould, it had become clear to all investigators that formative influences were continuing to operate. What remained to be determined were the relative contributions of catastrophes, chiefly volcanic activity and devastating atmospheric events such as cyclones and tsunamis (Japanese, "harbour waves"), and the unseen, mostly subliminal operation of forces deep within the earth.

By the final decade of the 18th century, the debate over earth formation had become seriously polarized. Werner's followers, from their adherence to Biblical doctrine and steadfast belief in post-diluvial rock formation from precipitation, were dismissed by their critics as Neptunists (after Neptunus, the Roman god of water), whereas those who were convinced that the earth's formative processes came mainly from volcanic action were in turn labelled Vulcanists (after Vulcanus, the Roman fire god). Later, with a deliberate sneer, they were derided by their arch opponent, the chemist and fundamentalist Anglican, Richard Kirwan, President of the Royal Irish Academy, as Plutonists (Pluton, the Greek god of Hades). Actually, the latter was a more accurate description, and became the accepted term. For nearly 50 years, from the final decades of the 18th century through the first three of the 19th, the debate continued, often with great intensity, with one crucial element yet to be discovered: the time required to create the earth's rocks and then to model the landscape.

A Radical Theory: Inner Pressure and Geological Processes

Throughout those decades, it was commonly believed that the earth was but 6000 years old. That figure had been calculated by Anglican Archbishop James Ussher of Armagh in Northern Ireland, who, from evidence within the scriptures, determined that Creation had taken place during Saturday afternoon on 10 October 4004 BC. Over four years, 1650–1654, he published his findings in the *Annales veteris et novi testamenti* (Historical records of the Old and New Testaments) and from 1701 the dates he assigned for each biblical event were inserted in the left margin of printed Bibles that were becoming ever more widely distributed as literacy spread. Yet clearly, at least for Plutonists, the figure was far too small. On 7 March 1785 came the greatest challenge to Biblical authority so far: on that day, the first half of a four-part *Dissertation on the System of the Earth, its Duration and Stability* by James Hutton was read to a meeting of the Royal Society of Edinburgh, followed by the second half a month later. That lengthy paper, more than 35,000 words, changed geological thinking forever.

A Scottish gentleman farmer, James Hutton (1726–1797) was an active member of the intellectual circles in Edinburgh that founded the Philosophical Society in 1738 which subsequently evolved into the Royal Society of Edinburgh in 1783. Hutton was on close terms with some of the leading Enlightenment thinkers of the city, especially philosopher David Hume, economist and professor of moral philosophy Adam Smith, engineer James Watt, professor of chemistry Joseph Black and his younger assistant James Hall. That particular group formed a small coterie—the Oyster Club—

which met periodically over a convivial supper to discuss the great issues of the day, of which geology was a major element, especially the debate developing between Neptunists and Plutonists.

On 7 March 1785, Joseph Black read the first part of a dissertation by Hutton to a meeting of the Royal Society of Edinburgh entitled a *Theory of the Earth; or an Investigation of the Laws Observable in the Composition, Dissolution, and Restoration of Land upon the Globe*. In that paper, Hutton set out to show, by a steady, methodical presentation of empirical evidence, that the Neptunian theory was untenable, and that earth processes could only be explained in terms of subterranean heat and fusion. Modelling of the landscape consequently came from catastrophic subterranean activity in which volcanoes were not mere epiphenomena as Werner taught, but general to the globe, and they acted as "spiracles to the subterranean furnace in order to prevent the unnecessary elevation of the land, and the fatal effects of earthquakes", thereby contributing to the formation of convoluted and twisted strata (Hutton 1788, pp. 238–239). In fine Humean fashion, Hutton inferred, from the visible evidence of ongoing processes of surface activity such as natural decay, soil formation, erosion, sedimentation, etc., there had necessarily been "an immense time required for this destruction of the land".

Warming to his central theme, and the evidence of "the relics of sea-animals of every kind in the solid body of our earth" and their orderly deposition, it was essential to put aside the Mosaic theory with its bare 6000-year time frame, which allowed the "beginning of man at no great distance", and clearly lacked congruence with visible evidence. Hutton's sustained argument was based on the abundance of "immense masses, which…appear to have been formed by the calcareous *exuviae* of marine animals". At the top of the Alps, as well as the Andes, shells and corals have been found that must have "been originally formed at the bottom of the sea". The vast calcareous deposits and limestone strata, he argued, were absolute evidence of "some consolidating power by which the loose materials that had subsided from water should be formed into masses of the most perfect solidity" (Hutton 1788, p. 209).

A month later, on 4 April, Hutton personally read the second part in which he examined the various processes that led to "congelation", and drew on the extensive experimental activity of James Watt and Joseph Black, who had already conducted experiments that resulted in crystalline fusion of pyrites, galena (lead sulphate) and quartz, among other ores, at extremely high temperatures. He proposed that there are only two ways by which rocks can become consolidated into hard masses: either by water or by fire, the latter acting by heat and fusion. He conceded that water certainly produced some effects whereby dissolved particles can be precipitated, but, he observed, not all chemical elements and compounds can be so dissolved, citing fluor (fluorine, CaF_2) and sulphurous, bituminous and siliceous compounds. His assertion that "no siliceous body having the hardness of flint…has ever been formed, except by fusion" was a direct attack on Neptunism (Hutton 1788, p. 214). Proceeding to list a large number of other minerals, which had also been fused by experimental heat, Hutton claimed to have proved that "those strata have been consolidated by simple fusion, and second, that this operation is universal in relation to the strata of the earth" (Hutton 1788, p. 225).

Hutton continued to deal with the fundamental issue of earth formation: the Mosaic theory—held by Neptunists as an article of faith—which he dismissed out of hand because there was, as many others before had observed, no place "to provide for the retirement of the waters of the globe". His argument asserted that the "operation by means of which masses of loose materials, collected at the bottom of the sea, were raised above its surface, and transformed into solid land" was simply due to "extreme heat [which] expanded with amazing force" and which continues "at present with undiminished activity…in the fulness of their power" (Hutton 1788, pp. 231–234).

Finally, Hutton covered the cyclic processes observable in the earth, as he termed them, decay and renovation. Those processes, consonant with the thought of the time, were evidence of "order and design, of provident wisdom and benevolence", of the earth, its plants and animals, for the benefit of mankind, ordained by the "Author of Nature" (Hutton 1788, p. 245). The antiquity of the earth was clearly evident: the fossils in the strata of "the former world must have been sustained during the indefinite succession of ages…a system by which they are intended to continue those revolutions". It is in vain, he concluded in his final paragraph, "to look for anything higher in the origin of the earth. The result, therefore, of our present enquiry is that we find no vestige of a beginning, no prospect of an end" (Hutton 1788, p. 255). Deluges and divine catastrophes were rejected as significant agents of change and the Biblical assertion that the earth and all of nature came into existence only 6000 years ago was now challenged by the revolutionary conception of time reaching back through uncountable eons.

Hutton's *Theory of the Earth* was published in 1788, which he elaborated in 1795 in a two-volume *Theory of the Earth* (a third volume was published posthumously a century later). In that subsequent work, the character of his deductive approach is well illustrated in his statement that it was not based on extensive fieldwork but rather generated out of an hypothesis, drawn from the observations of others, and a giant speculative leap: "I just saw it, and no more, at Petershead and Aberdeen, but that was all the granite I had ever seen when I wrote my *Theory of the Earth*. I have, since that time, seen it in different places; because I went on purpose to examine it" (Hutton 1795, I: p. 214). Hutton's two dense volumes were redrafted after his death in more popular, readable form by the mathematician John Playfair in 1802 as "Illustrations of the Huttonian Theory of the Earth" generating considerable support.

Hutton's theory, however, continued to be criticized for the next 20 years, chiefly by Kirwan from a theological standpoint, who attacked it for being atheistic. Some Neptunists, however, following Hutton, were beginning to waver as further proof of fusion from heat became advanced, chiefly by James Hall with the assistance of Watt and Black. In a series of some 500 experiments beginning as early as 1790 and continuing into the 1820s, Hall demonstrated that crushed granite and basalt could be melted in a high-temperature furnace and then allowed to cool slowly. His first significant report appeared in a *Memoir* to the Royal Society of Edinburgh in 1805 (Hall 1805, pp. 43–48), in which he concluded that "the stony character of lava is fully accounted for by slow cooling after the most perfect fusion". The way was now being prepared for the development of a theory of reef formation from volcanism and basaltic earth movements, and the complementary reef processes exhibited in the coral specimens collected by naturalists during their voyages of exploration.

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