Celebrating the age of the Earth

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Abstract: The age of the Earth has been a subject of intellectual interest for many centuries, even millennia. Of the early estimates, Archbishop Ussher’s famous calculation of 4004 BC for the date of Creation represents one of the shortest time periods ever assigned to the Earth’s age, but by the seventeenth century many naturalists were sceptical of such chronologies. In the eighteenth century it was Nature that provided the record for Hutton and others.

But not all observers of geology enquired about time. Many, like William Smith, simply earned a living from their practical knowledge of it, although his nephew, John Phillips, was one of the first geologists to attempt a numerical age for the Earth from the depositional rates of sediments. For more than fifty years variations of that method prevailed as geology’s main tool for dating the Earth, while the physicists constrained requirements for a long timescale with ever more rigorous, and declining, estimates of a cooling Sun and Earth.

In 1896 the advent of radioactivity provided the means by which the Earth’s age would at last be accurately documented, although it took another sixty years. Since that time ever more sophisticated chronological techniques have contributed to a search for the oldest rocks, the start of life, and human evolution. In the attempt to identify those landmarks, and others, we have greatly progressed our understanding about the processes that shape our planet and the Universe, although in doing so we discover that the now-accepted age of the Earth is but a ‘geochemical accident’ which remains a contentious issue.

Establishing the Earth’s age and chronology has been something of an intellectual baton passed from one academic creed to another as each seemed to offer new hope of solution or understanding. In the seventeenth century the Earth’s age was subject to the strictures of religious and social orthodoxy. The product of Creation, theological study offered one logical path to its understanding, but also to its containment. This pattern would repeat itself, as forces for an expanded timescale repeatedly did battle with those who thought the Earth relatively young. This was never simply a conflict between ‘progressive’ science and a resistant society, but rather a reflection of the path travelled by an idea through a complexity of beliefs, dogmas, theories, measurements and methodologies.

In the eighteenth century, Theories of the Earth marshalled existing evidence, scientific practice and analogy, to construct models for the origin and development of the planet. At the beginning of the nineteenth century, modern geology emerged as a rigorous and empirical field of study then centred on stratigraphy with its implied notions of relative age. This, when combined with the wide adoption of uniformitarianism, gave the science new and seemingly rational ways to think about time. But the new geologists were often reticent about discussing time in terms of years. By the 1860s, however, the subject added the great evolutionary debate to its intellectual baggage as T. H. Huxley defended Darwin’s billion-year estimate for natural selection. Now both biologists and geologists joined forces to demand a longer timescale which permitted the playing out of those evolutionary and uniformitarian processes necessary to explain the condition of the Earth.

However, the age of the Earth had acquired a new interest group. Applying theoretical ideas developed in the early years of the century, a number of respected physicists began to offer hope of at last calculating the Earth’s age in years. But if their calculations were correct, then those great underpinning theories of the natural sciences could not be. With the discovery of radioactivity in 1896, the future of the Earth’s age was firmly in the court of that emerging interdisciplinary subgroup, the geophysicists. In the twentieth century these extended the timescale

remarkably. With Einstein’s general relativity field equations, the topic was also returning to cosmology, to explanations of the Earth’s age in the context of the age of the universe, to the realm of astronomers.

What unifies these different approaches and their practitioners is their extrapolation of time from the study of process, whether that process was observable or modelled by theory. Early chronologers rigorously applied contemporary historiographic methods to chart the ‘progress’ of history. Later geologists would extrapolate the time necessary for shaping the surface of the Earth or for the deposition or erosion of observable strata. Biologists too envisaged a time-dependent process of evolution. Physicists made predictions and measurements from the physics of heat and radioactive decay, and astronomers deduced process from planetary construction and arrangement. In the relative calm of the early twenty-first century, in a field which has seen centuries of deep controversy, we should perhaps reflect upon the confidence our predecessors had in their age for the Earth. They too thought they had ‘got it right’.

**Chronologies and theories**

In one of his popular articles, Stephen Jay Gould (1993, pp.181–193) responded to James Barr’s (1985) definitive study of a great historical chronologer with a diatribe against previous ‘Whiggish’ interpretations of this early form of scholarship. The historiography of science had long rejected the notion of ‘progress’, of the past having been a succession of errors, but Gould was here talking to scientists who necessarily remained wedded to, and driven by, this concept of progress towards ‘truth’. Though not the first to do so, Barr saw chronologers not as religious dogmatists but as rigorous scholars working within the social and intellectual constraints of their time. They were participating in the earliest of historiographic practices – the construction of a linear timeline of events – which, in reconceived form, would later underpin the great stratigraphic enterprise of the nineteenth century.

Rees’s early-nineteenth-century *Cyclopaedia* separated ‘sacred chronology’ from other historical chronologies. Here chronology was ‘one of the eyes of history’ and not simply the study of ancient theological texts. Its potential sources were many:

> As its use is extensive, the difficulty of acquiring it is not inconsiderable. It derives necessary assistance from astronomy and geography, also from arithmetic, geometry, and trigonometry, both plain and spherical; and likewise from a studious and laboured application of various sources of information, supplied by the observation of eclipses, by the testimonies of credible authors, and by ancient medals, coins, monuments and inscriptions (Anon. 1819).

Chronologies were constructed as an analytical tool so as to distinguish ‘cause’ and realize a ‘chain of events’ (Anon. 1837, p. 131). To achieve this, their content was selective and thematic.

To discern the age of the Earth, the only ‘credible authors’ were those relating creation stories. The Bible, or rather the texts from which it was written, then became the primary historical texts, key sources for the interpretation of time. Historians generally point to Theophilus of Antioch, of the second century AD, as perhaps the first to use the Biblical record as a source for the construction of a chronology. The art of chronology, however, extended back long before the Christian era, often deriving ‘fabulous ages’ of hundreds of thousands of years for particular civilizations (Anon. 1819, 1833, 1849). In the sixth century BC Zoroaster, a religious teacher who lived in Persia (now Iran), believed that the world had been in existence for over 12,000 years; the Roman writer Cicero relates that the venerable priesthood of Chaldea in ancient Babylonia held the belief that the Earth emerged from chaos two million years ago, while the old Brahmins of India regarded Time and the Earth as eternal (Holmes 1913).

By the sixteenth century the Bible formed a core resource for the writing of histories in Europe. Of particular significance was the interpretation of the Second Letter of Simon Peter, which states ‘One day is with the Lord as a thousand years, and a thousand years as one day’ (2 Peter 3:8) (see also Dean 1981a; Oldroyd 1996a). It draws on Psalm 90 of the Old Testament, ‘The human condition’: ‘Lord … To you, a thousand years are a single day’. Chronologers read this literally, and made each of the six days of creation equivalent to 1000 years. The Biblical motivation for discussing the Earth’s limited age was to encourage the living of ‘saintly lives’. For here was not simply the birth but also the death of the Earth, the Judgement Day, which will ‘come like a thief, and then with a roar the sky will vanish, the elements catch fire and fall apart, and the Earth and all it contains will be burnt up’ (2 Peter 3:10). If this were not enough to encourage piety, Psalm 90 also pondered human mortality, ‘over in a trice, and then we are gone.’
AGES OF THE EARTH

Fig. 1. Oil Painting of Archbishop James Ussher in 1658. Reproduced by kind permission of the governors and guardians of Armagh Public Library.

Scholars and particularly the clergy – long an intellectual elite – used these 6000 years as a framework. The relative merits of the Hebrew Massoretic text, the Samaritan Pentateuch and Greek Septuagint were much debated, while later studies of other civilizations revealed even longer chronologies and other creation stories. Given the range of sources and scope for interpretation, it is no wonder that no definitive chronology was produced.

Undoubtedly the most famous chronology known to us today is that published in the seventeenth century by James Ussher (Fig. 1) but, as Fuller (2001) shows, he was not alone nor was he the most revered in his time (see also Anon. 1819, 1833). A brilliant scholar, Ussher had completed a draft whilst at Trinity College, Dublin, in 1597. He was then only 16 years old. Barr (1985) disentangled the complexity of Ussher’s work, of which his Creation date of 4004 BC is best known. This curiously high-resolution date is derived from traditional interpretations he had inherited, which placed 4000 years between the Creation and the coming of Christ, and an adjustment to take account of evidence that Herod (a contemporary of Christ) died in 4 BC. However, only one-sixth of Ussher’s chronology was concerned with the Bible, the rest was a history of classical times. That we know of Ussher, however, rather than one of the hundreds of other chronologers, is simply an accident of history (for which, see Fuller 2001).

For one group of scholars it seemed the answer might be found by undertaking comparative studies of published chronologies in order to locate sources of error and correction. William Hales’ three-volume New Analysis of Chronology (1809–1812) is an example which became very familiar to early-nineteenth-century British audiences, but he had predecessors and contemporaries across Europe (Anon. 1837, p.133; Davies 1969, p.13; Fuller 2001). From his own studies Hales preferred a creation date of 5411 BC. But by the time he published, chronologies, however useful they were for the construction of civil histories, were no longer restricting views of the age of the Earth. Indeed scholars had, for almost a century, taken the debate beyond the religious confines of orthodoxy. Davies (1969, p.16), for example, suggests that scepticism of established chronologies existed amongst seventeenth-century naturalists. Though such views were rarely committed to paper, he felt sure that the London coffee houses must have been alive with such talk. The devout John Ray (1627–1705), for instance, reflected upon the organic origin of fossils and considered the implications for time of the depths of sediments and rates of denudation – a recurrent theme in the centuries to come (Davies 1969, p.59; Dean 1981a, p.444).

Despite the enforcement of religious orthodoxy by the state (Davies 1969, p.11), freedom of expression about the origins and history of the Earth developed rapidly in the eighteenth century. In 1694, for example, Edmond Halley considered the implications of a comet impact on the Earth. He imagined an Earth repeatedly reborn following chaotic destruction. It seemed to support a view of an eternal Earth undergoing periods of dissolution and recreation – a notion then considered ‘one of the most dangerous of heresies’ (Kubrin 1990, p.65; Davies 1969, p.12). It was also a challenge to the British establishment, much like that presented by theories of biological transmutation a century later (Desmond 1989). Such ideas did not simply undermine religious teaching but proclaimed as a falsehood the natural social order into which the established church and wider society were divided. To counter such opinions of himself, which were likely to affect his career prospects, Halley then spent a good deal of his time pursuing evidence for a finite age of the Earth. For him, there were good socio-political reasons for wanting to discover a particular answer which reinforced accepted views (Kubrin 1990, p.65). Gould pondered one such of Halley’s observations (Gould 1993, pp.168–180). Understanding that the salts in the world’s oceans were delivered to the sea via rivers, Halley suggested that if the rate of contribution could be calculated then here would be a measure for the age of the Earth. It was an idea that was to resurface in the late nineteenth century in the hands of John Joly (Wyse Jackson 2001). What
surprised Gould was that Halley was considering a maximum age for the Earth, an argument against eternity, rather than a minimum. Thirty years later, following considerable social change, Halley was at last able to publish his paper discussing an Earth reborn without fear of social or religious retribution.

Halley’s contemporary, Sir Isaac Newton, also considered the Earth’s age and chronology, though without disrupting the traditional views of the Church. In his posthumous *Chronology of Antient Kingdoms Amended* he used astronomical calculations to correct those Greek and other ancient chronologies which were frequently used as historical sources (Newton 1728).

Rationalist Deism was an inevitable reaction to the strictures and assumptions of religious orthodoxy in seventeenth and eighteenth century Britain. It proved highly influential in intellectual circles across Europe and North America. For James Hutton, its most famous geological disciple, Nature provided a true record: the Earth’s timescale was indefinite. Hutton was born only a few years after it had been finally possible for Halley to publish his paper inferring a longer timescale, perhaps an eternity. Hutton, however, said nothing of eternity. On this, his great admirer, Archibald Geike, was emphatic (Geike 1899, p. 719; also Burchfield 1975; Dean 1981a, p. 454). Notable amongst Hutton’s critics was Jean André de Luc who, from the same record of Nature, found only concordance with Biblical chronology. For de Luc (discussed by Rudwick 2001) geomorphological processes created features in the landscape that were indisputably the product of time. If process rates were known then a mechanism for measuring time existed. It was this same kind of thinking which Georg Louis Leclerc, the Comte de Buffon, famously used to extrapolate a longer timescale of 75,000 years (discussed by Taylor 2001), a timescale which he still felt too short. Buffon applied measurement and reason, and promoted a theory based on contemporary empiricism (Buffon 1807).

Jean Louis Giraud, Abbé Soulavie (1752–1813), like Nicolas Desmarest (also Taylor 2001), interpreted temporal sequence from a study of volcanoes. In his book of 1791, he compared volcanic deposits to the Control of Acts, a recent piece of legislation which ensured that the dates of contracts would be registered such that originals could be verified. He also predicted the future role of fossils in determining the Earth’s chronology:

All these volcanoes and their products may be placed today in a certain order by reason of these curious ‘registries of control’ of nature. The study of these monuments is, in the mineral kingdom, the veritable art of verifying the dates of nature, as the study of plant or shell-bearing rocks is the art of verifying the dates and eras of the ancient history of organized beings in the kingdom of the living world (Soulavie 1791).

He used superposition of volcanic deposits, their relative state of preservation and comparative elevation above the sea as indicators of succession, but he was not suggesting the Smithian principle of characteristic fossils.

Throughout the eighteenth century, across the whole of Europe, Theories of the Earth mixed conjecture, religious orthodoxy and observation (Vaccari 2001) gives a wide overview). That the Earth had undergone a succession of ‘revolutions’ was a popular concept. It was critical to George Cuvier’s (1817) *Essay on the Theory of the Earth* which interpreted the succession of extinct animals preserved in the fossil record and the wild contortions of rocks which, following the arguments of Steno, were believed to have originally been deposited horizontally. But by the time Cuvier’s *Theory of the Earth* was published, the genre was attracting much criticism from a new breed of empiricist geologists.

**Relative age, uniformitarianism and time**

As geology emerged as a rigorous and self-contained science in the early nineteenth century, there remained a belief that a unifying theory might permit explanation of the geological world. Time, as a useful geological concept, however, did not emerge from theory but from observation. The stratigraphic work of William Smith (Fig. 2), Cuvier and Alexandre Brongniart, Thomas Webster and John Farey in the first two decades of the nineteenth century proved fossils as useful time markers. It was an idea that would develop rapidly in terms of its understanding and application throughout the first half of that century. Unlike Buffon and Cuvier (and indeed Webster), Smith’s goal was not intellectual or social (Knell 2000) but entirely practical (as Torrens (2001) demonstrates). The knowledge he developed resulted from attempts to solve the practical problems of coal prospecting. As Torrens shows, this was one of the major economic challenges of the period. What Smith actually thought of the role of time in causing the arrangement of fossils and strata is a matter for debate (Knell 2000; Torrens 2001; Fuller 2001). For the most part he was talking about the ‘natural order’ of strata, though we should
have no doubt that his views changed. Certainly by 1824 Smith’s work on the Yorkshire coast, was giving ‘strong confirmation to the geological axiom that “Deposits of equal antiquity enclose analogous fossils”’, as his nephew and co-worker, John Phillips (Fig. 2), reported to the Yorkshire Philosophical Society (Knell 2000, p. 148). That Smith should have co-authored such a statement is something most historians of Smith have previously denied. But as is apparent from Torrens’ paper, Smith’s ideas were never fully formed. When he and Phillips began their detailed study of the Yorkshire coast in the 1820s they were testing their knowledge of sequence and indicators, and the reliability of the Smithian method. What Torrens most clearly demonstrates is that in an era of frequent coal prospecting scandals it was easy to understand why Smith was revered by some and yet simply not believed by others. The risks were great and the Smithian technique was neither infallible nor at the height of its sophistication. In 1813, Ernst Friedrich, Baron von Schlotheim, like others on the frontline of the new science, still felt fossil-based chronology a possibility rather than a reality (Schlotheim 1813). George Greenough (Fig. 2) and a few others doubted it had any particular value at all. Schlotheim, like John Farey and later Von Buch, called for higher resolution studies of organic remains, as he felt these might reveal the epochs of revolutions in terms of spans of years. By the 1830s, chaotic fossil nomenclature was, more than anything, leading to stratigraphic imprecision. The British Association for the Advancement of Science charged John Phillips with the task of sorting this out (Fig. 2).

Phillips epitomized the empiricism which, it was claimed, had turned geology into a rigorous science. He made an entire career out of time, the kind of relative time which Callomon (2001)
now pursues. In the middle years of the nineteenth century, Phillips was producing endless tables of facts, believing, initially at least, that errors arose from omission and that comprehensive data would yield more accurate results. He was later to understand the error of this reasoning as the wealth of data he had generated was sometimes beyond human powers to process (Knell 2000). Phillips was so swept up in the mid-century fashion for statistics that one may feel somewhat surprised when Morrell (2001) tells us of Phillips’ reticence to commit himself to a number for the age of the Earth.

Though reticent, Phillips understood the human desire to create a scale for the chronology given by relative time. He knew all attempts were bound to fail due to countless factors that would corrupt and distort the figures. One could only expect ‘plausible inferences concerning the time elapsed in the production of stratified rocks’, nothing more (Phillips 1849, p. 795). However, ever willing to apply a little mathematics to philosophical puzzles, he made an attempt ‘in a strictly philosophical spirit’ in the Encyclopaedia Metropolitana. He considered a number of ways in which the problem might be resolved, including using upright fossil plant remains as evidence of rapid depositional events (such as the locally famous fossil tree trunks in the coal measures of Altofts, near Wakefield, which Phillips knew well). However, the most logical line of enquiry remained that which had attracted the attention of Desmarest, Soulavie, Buffon and de Luc, and which was now characterized by the uniformitarian principles of Charles Lyell (Fig. 2), John Playfair and Hutton: that is, the deduction of time from the products of geomorphological processes. Here he undertook a calculation of the time taken to deposit Coal Measure flagstones within which layers of rolled grains one-twentieth of an inch thick could be detected. A 40 ft thickness of rock implied 9600 layers. If each layer represented a tidal, then about 700 layers would result from annual deposition. Thus 40 ft of rock could be deposited in approximately 13.5 years. Half of the Yorkshire Coal Measures consisted of sandstones, some 1500 ft of strata in all. By this reasoning, deposition of the whole of the Coal Measures may have lasted 1000 years. Such figures, combined with Phillips’ belief that all strata ultimately originated as molten rock, made him think the Earth did have a finite age, a view he felt disagreed with Lyell (Phillips 1849, p. 798). However, by this time Phillips had read Joseph Fourier’s (1822) Théorie Analytique de la Chaleur (The Analytical Theory of Heat) and was, along with other ‘theorists’ (as Morrell (2001) reveals), foreseeing the conflict between the infinite timescale of uniformitarianism and the restricted needs of those theorizing on the physics of the Earth (as discussed by Brush 2001; Dalrymple 2001; Lewis 2001; Shipley 2001; Yochelson & Lewis 2001; Wyse Jackson 2001).

Some have suggested that, as the century wore on, geology continued to be threatened by conservative and speculative philosophy. Though Fuller (2001) sees in Leonard Horner’s 1861 address to the Geological Society of London remnants of religious orthodoxy snapping at the heels of science, Davies (1969, p. 210) was more dismissive. Was Horner ‘tilting at windmills’ or detecting a real threat in orthodox religion? More than a century later, geologists continue the same campaign while observers ponder the same question. By the middle of the nineteenth century, Victorian society was undergoing a crisis of faith, to which geology with its notions of endless time had contributed (see Dean 1981b). However, attempts were made to understand the Bible in ways acceptable to contemporary interpretations of the geological evidence. One came in the 1850s when Hugh Miller, the Scottish geologist and writer, attempted to reconcile the Genesis and the fossil record in The Testimony of the Rocks (1857) (Oldroyd 1996b). He explained Genesis Ch. 1 as a literally visual revelation, each ‘day’ corresponding to a geological period. Although popular in its day, it was ultimately insufficiently naturalistic for the scientists and too liberal an interpretation for the theologians.

However, by this time it was not religion that was restraining the age of the Earth, but the physics of heat and its implications for a cooling Earth. Now Lyell’s most fundamental principle – that of uniformitarianism – and all that rested upon it, seemed under threat. With Archibald Geikie in the ascendency as Britain’s pre-eminent geologist, an unbridled supporter of Lyell and Hutton, the geologists were not going to take any restrictions on the age of the Earth lying down. Amongst his many arguments Geikie used denudation rates, rather than rates of sedimentation, to discuss the scale of geological time. Based on empirical data for the mean height of the continents, and fluvial sediment and solution loads, he predicted the complete wasting of Europe in just 4 million years, North America in 4.5 million and South America in 7 million. It demonstrated that rates of denudation were not as slow as usually stated and that vast quantities of time were not required to produce considerable change to the surface of the Earth (Geikie 1868). It was not that Geikie...
wanted a young Earth but that a young Earth did not undermine uniformitarianism. Evolutionary biologists were talking in terms of Darwin’s estimate of 1000 million years for the record of natural selection, time the geologists were willing to give. As Huxley remarked in defence of geology, ‘Biology takes her time from geology’ (Huxley quoted by Desmond 1994, p. 370). The physicists, led by William Thomson – later Lord Kelvin – and his collaborator Peter Guthrie Tait, were not followers of Lyell or Darwin.

The storehouse of creation

The closing decade of the nineteenth century saw the start of a scientific revolution that was to impact on geology in a way that would transform it forever and prepare it for the definitive ‘revolution’ that occurred in the 1960s. By 1893 debate between geologists and physicists about the age of the Earth was at its peak. The ages determined by geologists, using empirical methods and observing Earth processes, ranged from 3 million years ‘for the whole incrusted age of the world’ (Winchell 1883, p. 378), to Wilber John McGee’s 1892 value of 15 billion years for the whole age of the Earth, of which 7 billion had elapsed since the end of the Palaeozoic (Yochelson & Lewis 2001). These extreme values were largely unacceptable to both geologists and physicists, and did nothing to bring the two sides into closer agreement, although the urgent need for a reliable timescale was becoming more and more evident: ‘How immeasurable would be the advance of our science could we but bring the chief events which it records into some relation with a standard of time!’ (Sollas 1900, p. 717).

Lord Kelvin’s interest in the age of the Earth had been prompted by his work on the age of the Sun’s heat. He considered that the Sun, ‘assumed to be an incandescent liquid’, must obey the laws of thermodynamics, therefore it could not continue to radiate sunlight for ever unless it was being provided with energy. Since there was no evidence for this energy, there was no alternative – it must be cooling down – and the inevitable result of cooling was that the Sun had a finite life. In this conclusion Kelvin was supported by astronomers.

Given these apparently irrefutable circumstances, it is not surprising that when Charles Darwin, in the first edition of On the Origin of Species, published his estimate of 300 million years for erosion of the Weald, a section relatively high up in the geological sequence, that Kelvin’s response was dismissive: ‘What then are we to think of such geological estimates as 300,000,000 years for the “denudation of the Weald?”’ (Thomson 1862, p. 391; also Morrell 2001). Since the age of the Earth was constrained by the age of the cooling Sun, it was only to be expected that its inhabitants ‘…cannot continue to enjoy the light and heat essential to their life, for many million years longer, unless sources now unknown to us are prepared in the great storehouse of creation’ (Thomson 1862, p. 393).

Within a month of questioning Darwin’s estimate in public, Kelvin delivered his now famous attack on geologists and their methods for determining an age for the Earth that ignored the laws of thermodynamics.

At that time Kelvin proposed the Earth’s age to be between 20 and 400 million years (Thomson 1864), but he found the problem so interesting that over the following three decades he continued to pursue it, confessing that he ‘would rather know the date of the Consistentior Status than of the Norman Conquest’ (Thomson 1895a, p. 227). The Consistentior Status was considered to be the time when the molten Earth had first acquired a solid crust. As more data became available Kelvin reduced his estimate first to 100 million years (Thomson 1871), and then, in 1893, to only 24 million (Thomson 1895b) when new results on the melting temperature of rocks became available (King 1893). This new age concurred well with the age of the Sun, reckoned to be 20 million years. To the physicists, the inevitability of the Sun’s decline was a compelling reason for a young Earth, and the fact that the two ages, Earth and Sun, now gave consistent results was conclusive proof that both were right. There was little for the geologist to argue against, except to suggest to the physicist that ‘there may be an error somewhere in his data or the method of his treatment’ (Walcott 1893, p. 639).

The effort to quantify geological time affected both the theory and practice of geology and was largely responsible for it maturing into a professional scientific discipline. Up to that point, geologists had worked out their estimates for the age of the Earth from their empirical observations of sedimentary processes, based on the uniformitarian premise that the rates of these processes did not vary over time. It was largely the work of Kelvin that made clear to geologists the need for quantification and it was he who set them on a path which observed the laws of physics, from which they have subsequently deviated little. A rigid adherence to Lyell’s uniformitarian interpretation of geology was no longer possible, and although not all physicists were united in their interpretation of Kelvin’s data, as is evident from the views expressed by his former student John Perry (Shipley 2001),
they were, on the whole, agreed on the need for geologists to abandon their dogmatic attitudes. It was Perry, in fact, who complimented Kelvin in *Nature* for his exposé of uniformitarianism: ‘Lord Kelvin completely destroyed the uniformitarian geologists, and not one now exists. It was an excellent thing to do. They are as extinct as the dodo or the great auk’ (Perry 1895, p. 227).

That same year, 1895, William Röntgen discovered X-rays and the following year Henri Becquerel detected similar rays being emitted from uranium. The decade of discovery that ensued was a time unparalleled in the history of science (Lewis 2001). The speed at which new discoveries were made about the atom unravelled the whole fabric of physics, and a completely new design was needed to build it back up again. This new form of energy at last explained the discrepancy between the long timescales observed by geologists, and the short one predicted by Kelvin. For even if the Earth was still cooling from a time when it had been a molten globe, the heat generated within the Earth by radioactive decay had counteracted that cooling for hundreds of millions, even billions, of years.

Based on the accumulation of helium, a by-product of the decay process, in 1904 Ernest Rutherford (Fig. 3) determined the very first radiometric date: a fergusonite mineral gave an age of 500 Ma. More than forty years after Kelvin’s pronouncement that the Sun would not keep shining unless new sources of energy ‘now unknown to us are prepared in the great storehouse of creation’, Rutherford was to opportunistically turn this phrase to his advantage in order to placate Kelvin, whose age for the Earth was now demonstrably in error: ‘That prophetic utterance refers to what we are now considering tonight, radium!’ (Eve 1939, p. 107). But Kelvin died three years later, having never fully accepted that a new source of heat had indeed lain in the great storehouse of creation. As Martin Rees (2001) explains, most elements, particularly the heavy ones like uranium, form during a supernova explosion, the gaseous debris from which ultimately resulted in the formation of our Solar System. Thus stellar nucleosynthesis could be viewed as Kelvin’s ‘great storehouse of creation’ in which all elements on Earth are prepared.

![Fig. 3. Ernest Rutherford (1871–1937) (right), who determined the first radiometric date, with Hans Geiger, in their laboratory at Manchester University, around 1912. Credit: Science Museum/Science and Society Picture Library.](http://sp.lyellcollection.org/Downloaded from http://sp.lyellcollection.org/)
Throughout history, there have always been those slow to accept changes to the status quo, and who fiercely resist innovation, particularly when, like radioactivity, it is rapidly introduced and means the discarding of many strongly held beliefs. Having desired, in Lyell’s day, an Earth of almost infinite duration, geologists fought Kelvin for fifty years to be allowed an Earth that was even a hundred million years old. Within a few years of Rutherford’s first radiometric date, it became clear that, after all, geologists could again have an Earth of almost limitless extent, but now the demand was for less time. They were being asked to accept a ten-fold increase – an Earth that was more than a billion years old: just where were all the sediments needed to fill such enormous amounts of time?

During this period of transition, two men were particularly prominent in developing the science of geochronology. Today John Joly is famous for his attempts to date the age of the Earth from the sodium content of rivers, but he was also a man with an extraordinary range of interests and abilities (Wyse Jackson 2001). Joly was quick to grasp the principles of radioactivity and to apply them to geological problems, but his inability to accept the long timescales being indicated by the method was typical of many of his generation. It required someone younger, with an open mind unfettered by the need to maintain political prestige, to solve the new problems. Arthur Holmes’ additional advantage over many of his geological contemporaries, was that he had a background in physics, but being familiar with all the old methods used to estimate the age of the Earth, he also understood the difficulties being encountered by geologists:

The surprises which radioactivity had in store for us have not always been received as hospitably as they deserved. With the advent of radium geologists were put under a great obligation, for the old controversy [the need for a long time scale] was settled overwhelmingly in their favour. But the pendulum has swung too far, and many geologists feel it impossible to accept what they consider the excessive periods of time which seem inferred (Holmes 1913, p. 167).

For more than four decades Holmes was in the vanguard of geochronology, and during that time he contributed more to understanding that science than any other single individual. He pursued an almost evangelical crusade to persuade geologists and the world at large, of the value of radioactivity as a means for measuring the age of the Earth, and an Earth of great antiquity (Lewis 2001).

In the United States, rejection or acceptance of ideas about radioactivity and its application to geological problems progressed at much the same rate as it did in England, although in the first quarter of the twentieth century America lagged behind by a year or so. Since most of the work on radioactivity was then being done in Europe, time was needed for ideas to travel by boat across the Atlantic and for the more important papers to be reproduced in American journals (Yochelson & Lewis 2001). But by the early 1930s, most scientists in both countries essentially accepted the geological timescale provided by Holmes, and little reference was made to any timescale provided by sedimentation or denudation rates. Now only the astronomers seemed to question the validity of radiometric dates (Brush 2001).
element had been around for a decade previously (Kaufman 1982). The process of ‘discovery’ is in fact rarely a ‘Eureka’ moment, being almost always one of a gradual evolution of ideas—the replication of memes (Dawkins 1989) that occasionally mutate. Scientists, however, do like to attribute discoveries to an individual who was first. After all, one of the basic priorities of research, particularly these days, is to be able to claim credit in the intellectual rat race. The Theory of Plate Tectonics should rank alongside Darwin’s Theory of Evolution and Einstein’s Theory of Relativity, but perhaps because it cannot be attributed to any one individual, it is somehow assigned to a lower rank.

Regardless of who developed the model for dating the age of the Earth, once it was in place all that remained was for techniques to progress to a point where accurate data could be obtained and plugged into the model to give the correct result. Claire Patterson (Fig. 4), so named on his birth certificate but who frequently called himself Clair in an attempt to avoid the gender confusion (L. Patterson, pers. comm. 1999), was another whose mass spectrometry skills had been honed on the Manhattan Project. In 1956, after a decade spent developing techniques to measure minute amounts of lead, this skill enabled him to finally date the ‘time since the earth attained its present mass’ (Patterson 1956, p. 236). He resolved it to be $4550 \pm 70$ Ma. After centuries of controversy, it may appear that the final event went almost unnoticed, but it is only with hindsight that we now know Patterson was ‘right’. At the time, it might only have been one more of the many recent attempts to get it right.

**Ages of the ‘oldest’**

There is something in the human psyche that drives us to look for extremes—the first and last, the highest and lowest, largest and smallest, youngest and oldest. With the search for the age of the Earth ticked off that list, we have looked for other extremes. Biologists search for the first signs of life and anthropologists for the first humans; in astronomy it is the furthest stars; in geology the oldest rocks.

Since development of the Theory of Plate Tectonics, we have progressed to a remarkable understanding about the way the Earth has evolved. Despite this, we still have a rather hazy view of those first 500 million years,
although the hope is that the oldest rocks of the planet will carry a 'memory' of the processes that occurred hundreds of millions of years before their formation. Evidence from zircons that give an age of 4.4 Ga, suggests that crust was forming on the Earth's surface soon after accretion (Kamber et al. 2001), which is considered to have lasted some tens of millions of years (Hofmann 2001). But 'accretion' seems to have persisted in the form of 'bombardment' for at least another 500 Ma, as massive impacts, known to have bombarded the Moon until 3.9 Ga, presumably also hit the Earth. No evidence is found on Earth for this bombardment, but the apparent lack of survival of any in situ crust older than 3.8 Ga (Kamber et al. 2001) strongly supports the theory. The race to find older and older crust appears to be limited by this bolide barrier. However, history reminds us that for thirty years (1911–1941) the age of the Earth remained static at 1.6 Ga because, during all that time, no minerals were found that indicated it might be any older. But in 1941 discovery of the Manitoba pegmatite, that gave an age of more than 2.2 Ga (Nier et al. 1941), made it apparent that the Earth was actually much older than anyone had hitherto realized. Thus the search for older and older crust should not be discouraged!

The biologist's search for the start of life on Earth, asks not only the question 'when?', but also 'how?'. Was it in the murky primordial soup, or on the back of one of those massive bolide impacts? Evidence for life is now found in the oldest known sedimentary rocks that are 3.7–3.8 Ga (Kamber et al. 2001). As flexible and durable as life seems to be, a continued search may well push that boundary back even further.

Searching for our ancient hominid ancestors is a topic of particular interest to us all, and perhaps it is a mark of the success of archaeology to capture the public's imagination, that when asked the question 'What technique is used to date age of the Earth?' the vast majority will answer 'carbon dating'. In the last fifteen years, refined archaeological dating techniques have immeasurably improved our ability to understand the time-scale of human evolution, particularly for the last 200 000 years (Stringer 2001). The new dating techniques that facilitate this understanding are the direct descendents of those established by the early pioneers in the last century who worked so hard to launch geochronology as a science. Now it is impossible to imagine how we would manage science without them.

Chronology is a crucial tool for the understanding of many disciplines. Being able to date events tells us much about the processes that enabled them. For example, the key to unlocking geology's unifying theory was development of a timescale of magnetic reversals seen on the floor of the oceans. Immediately it became clear that the youngest rocks were nearest to the central ridge, while the oldest were furthest away and adjacent to the continents – so the oceans really were opening, and the continents really were drifting apart! Sea-floor spreading, hitherto just a theory, became a fact.

Similarly, as Brush (2001) discusses, when the value for Hubble time, which provides an age for the Universe, was seriously underestimated in the 1930s and '40s, it resulted in a Universe that was younger than the Earth and stars it contained. Astronomers then sought a range of models, or processes, in an attempt to explain this discrepancy. For example, the fact that the timescale problem did not exist in the Steady-State Theory was one of its advantages. But because the timescale was wrong, so too were the processes used to explain formation of the Universe. Until the 1950s, Holmes and his colleagues, with their persistent and consistent dating of minerals from Earth, continued to be a thorn in the side of astronomers, in much the same way that geologists had been a thorn in the side of physicists during the previous century. It was not until the late 1950s that the Hubble constant was revised and provided a more realistic age for the Universe, which then facilitated development of current models for its evolution. Today, some astronomers claim that the Big Bang Theory explains evolution of the Universe to such an extent that they can 'place 99 percent confidence in an extrapolation back to the stage when the Universe was one second old' (Rees 2001). In the light of history, and all the bold statements discussed in this volume that have subsequently proved incorrect, this is a brave assertion.

**Conclusion**

The value that Patterson determined for the age of the Earth has not changed in nearly fifty years, beyond that allowed for by his error range. Compatible with ages of meteorites and the Moon, it now seems a consistent and stable number, but is it? Like an explosive volcano, the age of the Earth debate did not die, it just lay
dormant for fifty years until science had progressed sufficiently to question the underlying assumptions on which it was based. Our improved understanding of the extreme chemical differentiation that occurred during separation of the crust from the mantle reveals that although the mechanisms for enriching uranium and lead in the crust are quite different, the result is that, on average, the overall enrichment is much the same for both elements (Hofmann 2001).

As Hofmann explains, although this ‘geochemical accident’ served Patterson well and apparently provided him with the ‘right’ answer, terrestrial lead isotopes, such as those that contributed to the ocean sediments used by Patterson to represent ‘average Earth lead’, can only provide an approximate age. The ages of other events, such as formation of meteorites now considered to be 4.56 Ga, the timing of core differentiation that occurred during separation of the crust from the mantle reveals that although the mechanisms for enriching uranium and lead in the crust are quite different, the result is that, on average, the overall enrichment is much the same for both elements (Hofmann 2001).

The extinct decay products of short-lived radioactive nuclides are now being used to interpret the chronology of the earliest history of the solar system, so perhaps they will also provide further constraints on the formation history of the Earth. Until then, the age of the Earth remains controversial and the search for a refined value continues. It could make for interesting discussion at the turn of the next century.

We would like to thank all the authors who have contributed to making this volume the rich and varied book it has become, and on whom we have extensively drawn for this paper. As editors, we would like to thank not only the referees of this paper, M. Taylor and M. Stoker, but also all those referees who have willingly given of their time and expertise to comment on the wide range of papers put before them. Thank you all. It made our task a lot easier!

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