# Chapter 14

## Kelvin and the age of the earth

J.A.T. Halls[1] & D. Wilkie[2]
[1]*Brunel Institute for Bioengineering, Brunel University London, United Kingdom.*
[2]*Formerly of British Nuclear Fuels, United Kingdom.*

### Abstract

'For having, in the natural history of this earth, seen a succession of worlds, we may from this conclude that there is a system in nature; in like manner as, from seeing revolutions of the planets, it is concluded, that there is a system by which they are intended to continue those revolutions. But if the succession of worlds is established in the system of nature, it is in vain 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.' James Hutton, Theory of the Earth, 1788.

'I think we may with much probability say that the consolidation cannot have taken place less than 20,000,000 years ago, or we should have more underground heat than we actually have, nor more than 400,000,000 years ago, or we should not have so much as the least observed underground increment of temperature.' Sir William Thomson (Lord Kelvin), On the Secular Cooling of the Earth, 1862.

'I do not presume to throw the slightest doubt upon the accuracy of any of the calculations made by such distinguished mathematicians as those who have made the suggestions I have cited. On the contrary, it is necessary to my argument to assume that they are all correct. But I desire to point out that this seems to be one of the many cases in which the admitted accuracy of mathematical processes is allowed to throw a wholly inadmissible appearance of authority over the results obtained by them. Mathematics may be compared to a mill of exquisite workmanship, which grinds you stuff of any degree of fineness; but, nevertheless, what you get out depends on what you put in; and as the grandest mill in the world will not extract wheat-flour from peascods, so pages of formulæ will not get a definite result out of loose data.' Thomas Henry Huxley, Address to the Geological Society, 1869.

## 1 Early estimates

Speculation on the age of the earth has existed for millennia. Many, like Aristotle have suggested that it is infinitely old, but most in early years have taken it to be finite and essentially unchanging albeit with variations in weather and with occasional volcanic eruptions and earthquakes superimposed.

WIT Transactions on State of the Art in Science and Engineering, Vol 89, © 2015 WIT Press
www.witpress.com, ISSN 1755-8336 (on-line)
doi:10.2495/978-1-84564-149-8/015

The development of Judaic religions with a single deity who created the world and all things in it imposed finite limits on the existence of the Earth. The future limit lay in the hands of the deity and was therefore inherently unpredictable, but the creation was a matter of biblical record and could therefore be deduced by reference to the books of scripture.

It was only natural that someone would attempt this calculation, at least to define the date of the creation. Several attempts were made including that of Theophilus, 7th Bishop of Antioch (see Albritton [1]) who carefully traced the biblical records to arrive at a date for the creation of 5529 BC. Others came to similar conclusions including Julius Africanus who held that Christ had come during the sixth 'day' of the cosmic week, where each day lasted for a 1000 years.

Several quantitative estimates of the earth's age were made in the 17th century, the most famous and oft quoted being that of the Irish protestant Archbishop of Armagh and Primate of all Ireland James Ussher (1581–1656). With considerable care and outstanding scholarship, he used historical records of events such as the deaths of Julius Caesar in 44 BC and of Alexander in 323 BC to establish a definitive chronology [10]. Beyond the reign of Nebuchadnezzar around 600 BC, he relied on biblical texts and chose the version of the Hebrew bible prepared by the Masaretes, which is the basis of the modern Hebrew bible. From all this, he deduced that creation took place at nightfall preceding 23 October 4004 BC, that is, 4000 years before the birth of Christ. His chronology was added to the Authorised Version of the bible at one stage and is still included in the marginal annotations of Gideon Bibles. Many, including Charles Darwin (see Fig. 2), thought it was part of the authorised bible and that may be why some Christian commentators have come to accept it as precise, despite information from geology and evolution and the fossil record.

Possibly the first attempt to describe a non-biblical origin of the Earth came from Benoit de Maillet [11]. His account was not published until 1748, 10 years after his death, having been circulated amongst his contemporaries as a handwritten manuscript, since de Maillet was well aware of the power and influence of the church and the views that they would take of his work. His theory was based on the assumption that at some time in the past the Earth had been completely covered in water, from which man and the animals had developed and emerged onto dry land as the level of the oceans dropped over time. From observations of the rate at which sea levels were declining, and also evidence of ancient cities and settlements which were originally built at sea level but were now up to 6000 feet above the ocean, he determined that the age of the oldest of these settlements must be around 2.4 Ma.

A more practical approach to the problem was taken by George-Louis Leclerc, Comte de Buffon (1707–1788). Newton, in his *Principia Mathematica*, had established that the Earth must once have been molten and that it had cooled in the shape of an oblate spheroid. On the basis of the time, it took a 1 inch sphere of iron to cool from red heat he calculated that a mass of iron the size of the Earth would take 50,000 years to cool from red heat, although he felt that this figure was likely to be an underestimate and suggested that some practical experiments would be advisable. Buffon was attempting to compile an encyclopaedia of all knowledge of nature and natural history. This *Histoire Naturelle, Generale et Particuliere* was to occupy 50 volumes with numerous additions, although only 35 volumes were completed in Buffon's lifetime. The twentieth volume, Epochs of Nature (1778) [12] was concerned with a history of the development of the Earth from a molten globe to the present day. He based his calculations on experimental data, using 10 spheres of iron up to 5 inches in diameter in ½ inch increments, specially manufactured at his own foundry so that he could be sure of their quality and uniformity. He heated the spheres to white heat and timed the cooling to red heat, absence of glow and to be holdable in a bare hand. From this he calculated that a mass the size of the earth would cool to below incandescence in 42,964 years and to its present temperature in 96,670 years. After making adjustments for the delaying effect of the sun's heat and also some historical data he produced a revised figure of 74,832 years, although he never felt that this really allowed sufficient time for observed geological formations such as the tremendous thickness of sedimentary rocks exposed by the Alps. Unpublished manuscripts, however, show several longer chronologies, even up to 3 Ma [1].

A more philosophical approach was taken by Immanuel Kant (1724–1804) who supposed that divine creation lay in the marvellous creation of laws of nature which by their simple and consequent operation would result in the formation and development of the universe according to God's divine plan. Where Newton had declared that his laws could not explain the development of the planetary system and that it had been given its present structure by God, Kant in 1755 [13], developing on the work of the English astronomer Thomas Wright (1711–1786), used Newtonian mechanics to describe not just the development of the solar system, but the development of the entire universe. He considered that while the past history of the Universe must be finite, the future development was infinite in its extent. His ideas are not totally irreconcilable with modern theories of the development of the universe.

## 2 The development of uniformitarianism

Two theories, the Neptunian and the Plutonic, were propounded based on the Earth that evolved through a series of catastrophes. Georges Cuvier (1769–1832) and Jean-Baptiste Lamarck (1744–1829) espoused and developed the Neptunian school of geological development, although they differed on the interpretation of the Noachian flood. The Neptunian school in general preferred to favour periodic catastrophic flooding as the major cause of geological change. By invoking these major upheavals, it became possible to account for the observed geological development without the need for extensive periods of time.

The opposing theory came from the Plutonist school who favoured Buffon's fiery beginning for the Earth and assumed that the Earth was either molten at its centre or at least had a molten shell around a solid core. This molten region was then the cause of volcanoes and earthquakes in shaping the planet.

It was not until the second half of the eighteenth century that a serious geological examination took place. This was due to Edinburgh born James Hutton (1726–1797, see Fig. 1), who after studying medicine at Edinburgh, Paris and Leyden took up agriculture in Norfolk and afterwards on his estate in Berwickshire. He returned to Edinburgh in 1768 where he joined up with other intellectuals including Joseph Black the founder of quantitative chemistry and discoverer of latent heat, specific heat and carbon dioxide; philosopher Adam Ferguson, a member of the 'common sense' school of philosophy established by John Reid; John Playfair, mathematician and physicist; and Sir James Hall, geologist. These and others including David Hume and Adam Smith formed what was designated in the late nineteenth century as the Scottish Enlightenment.

Hutton lived in a house on St. John's Hill, 50 yards south of the Royal Mile in the Old Town of Edinburgh where the intellectuals would meet in each others' homes to discuss their new

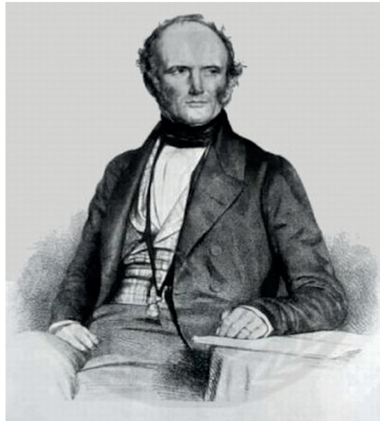

Figure 1: James Hutton (left) and Charles Lyell (right).

ideas. From his house, he would be able to see Arthur's Seat and Salisbury Crags, volcanic outcrops where he would make his initial discoveries. After a number of years visiting many sites in Scotland and England during which he collected samples and developed his theories, he presented his ideas to the Royal Society of Edinburgh in 1788 in *A Theory of the Earth* [7] which was later expanded to a two volume book in 1795 [14]. (A third volume, was published much later by Sir Archibald Geikie in 1899.) In these two volumes he demonstrated that the internal heat of the earth caused intrusions into the crust, the molten rock then solidifying and forming granite. His theory can be summarised as follows:

- There occurs gradual degradation of the land by erosion, particularly through river action.
- The eroded matter is transported out to sea and deposited as sediments.
- The sediments consolidate at the bottom of the sea. In due course these sediments are elevated by land upheavals which form new land surfaces which in turn are subject to erosion producing repetition of the cycle.

Hutton concluded that he could see 'no vestige of a beginning and no prospect of an end'. 'Thus the present is a key to the past.' As a result, the theory became known as uniformitarianism. His ideas were made accessible to a much wider audience by the publication in 1802 of John Playfair's book *Illustrations of the Huttonian Theory of the Earth* [15].

Hutton's theory did not necessarily rule out a creation but indicated an equilibrium state extending into the distant past. His ideas were, of course, at variance with the biblical chronology expounded by Ussher and were opposed by the church and by geologists throughout Britain and Europe who generally held theological views in these times. However, the ideas survived their criticisms, forming the basis of modern geology of which Hutton is generally accepted as the founder.

In 1824 John Coleridge, newly appointed editor of the *Quarterly Review*, asked the young barrister, Charles Lyell, (see Fig. 1), to prepare articles for the journal. Lyell was much more interested in geology than in law but had seen no way to make a good living from the subject so the possibility of writing about geology and being paid for it was a godsend. Over the next 2 years, Lyell produced five articles including a lengthy and extensive review of the Geological Society's Transactions; he was familiar with these having been elected a secretary of the society in 1823. Late in 1827 he began writing his *Principles of Geology* [16], which was to become one of the standard texts in the subject and which would influence an entire generation of geologists. The first volume was issued in 1830 and the entire work was continuously revised and extended throughout his life. He accepted, with some reservations, the principles of Huttonian theory as propounded by Playfair and gently but firmly repudiated the claims of the catastrophists. His belief was that the geological evidence firmly proclaimed that geological development had taken place over periods of time which were vast in comparison to historical time. He further believed that the processes at work in the past were not essentially different from the processes which can be observed today. He did not make any attempt to quantify the age of the Earth but showed from descriptions of geological processes now in action that these were sufficient to account for the geological record given sufficient time in which to operate.

Lyell was not strictly an evolutionist but his model of the development of the Earth was one of gradual change over long periods of time. This suggestion of gradual change may have influenced the thinking of Charles Darwin who took a copy of volume 1 of Lyell's *Principles* with him on his voyage on the Beagle. Although Darwin had had only a relatively superficial training in geology, he made extensive geological observations on his travels. His ideas on the origin and development of species developed over a long period of time and was outlined in a pair of unpublished essays written in 1842 and 1844. The main treatise *On the Origin of Species* was not published until 1859 [17] and even then was considered to be the abstract of a much more extensive work. The similar theories of Wallace, however, led his friends, especially Charles Lyell and Joseph Hooker, to push him to a joint presentation of his ideas and an earlier publication than he would have preferred [18].

The theory of the origin of species through a process of natural selection relied in large part on the availability of extensive periods of time in which to operate and Darwin cites Lyell to

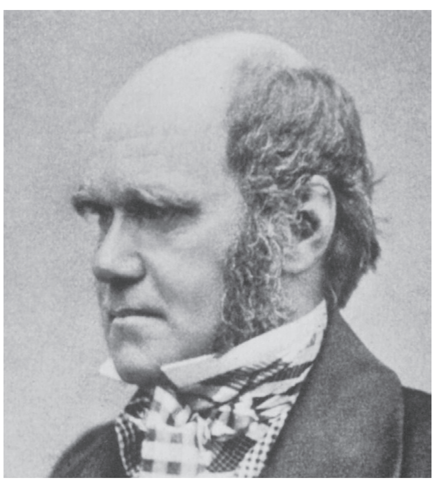

Figure 2: Charles Darwin.

support the thesis that there would have been plenty of time available. In the first edition of Origin, he also provided a brief illustration to support this contention. He estimated that the denudation of the Weald of Kent must have taken something around 300 Ma and that this represented but a part of post-Cambrian time. As a brief aside we must throughout bear in mind the distinction between estimates of times *since* the Cambrian as evidenced by sedimentary deposits or rates of erosion – the geological stratification is unreliable for pre-Cambrian times – and estimates of the time since the Earth cooled from a molten globe which must include all of the pre-Cambrian epoch in addition.

Darwin's estimate was provided, essentially, as an illustration. He was clearly in no doubt that sufficient periods of time were available. However, in the controversy generated by Origin this estimate was pounced upon and extensively criticised to such an extent that Darwin removed the reference from the second and subsequent editions, Although he still cited Lyell as support for the claim that the availability of time was not an issue.

Darwin's health had suffered badly as a result of his voyage and he found visits to London to be very debilitating. He was therefore not well placed to defend his very controversial theories. The role of defender was therefore taken by his friend and adviser Thomas Henry Huxley.

Huxley was already becoming a very influential figure and was to become even more so. The son of a schoolmaster in Ealing he had trained as a surgeon and got an appointment as a surgeon's mate in the Royal Navy. He served originally at Haslar and was then appointed to be Surgeon on a voyage to the South Seas. On this voyage, he made a detailed study of marine invertebrates, sending reports back to London. On his return, after some disputes with the navy about being paid to develop his observations, he was awarded a medal by the Royal Society and later was appointed Professor of Natural History at the School of Mines. This was the start of a long and influential career during which he was instrumental in developing the principle that science should be a recognised profession. He formed the X-Club in association with a number of equally erudite friends and this group held great power over the scientific community in London.

## 3 Lord Kelvin

William Thomson, later to be Lord Kelvin, had a very different background, having a classical, if precocious, education leading to a degree from Cambridge, and eventually with the aid of some political manoeuvrings, the chair of Natural Philosophy at Glasgow [19]. A condition of his appointment was that he should, within a month, write an essay in Latin on the movement of heat through the body of the Earth. He was obviously dissatisfied with this essay since he burnt it immediately after its acceptance. The essay developed a theme which he had originally enunciated in the *Cambridge Mathematical Journal*. In a paper of 1842 'On the linear motion of heat' [20] he considered the motion of heat in an infinite solid, developing an equation from which it would be possible to find the temperature at any point a given distance from the zero-plane at a given time. This paper developed in some detail the work of Fourier and was the basis for much of his later work on determining the Age of the Earth. It was followed in 1844 by a 'Note on some Points in the Theory of heat' [21]. This second paper considered the problem of the motion of heat in solid bodies given an arbitrary initial distribution. Thomson also considered the case of negative values for time, that is, given the present conditions, can we deduce the conditions in the past? He considered three classes of cases depending on the degree of convergence of the terms in the controlling expression. He concluded that in one case it would be possible to assign a finite age given the initial distribution; in another it would not be possible and in the third the distribution at time zero must be an initial distribution which could not have been the result of any previous distribution of heat.

The importance of these two papers and the development in his inaugural essay can be seen from the note which he attached to the paper when it was included in his volume of reprints:-

'An application to terrestrial temperature of the principles set forth in the first part of this paper relating to the age of thermal distributions, was made the subject of the author's Inaugural Dissertation on the occasion of his induction to the University of Glasgow, in October 1846, De Motus Caloris per Terrae Corpus; which, more fully developed afterwards, gave a very decisive limitation to the possible age of the earth as a habitation for living creatures, and proved the untenability of the enormous claims for TIME which, uncurbed by any physical science, geologists and biologists had begun to make and to regard as unchallengeable'.

Only one page of draft of that inaugural essay remains, heavily corrected by his father:-

'De Distributione Caloris per Corpus Terrae.

In caloris theoria mathematica, problemata saepe pro-ponuntur in quibus data temperaturae distributione in initio, distributio in quolibet temporis sequentis puncto invenienda est In plurimis horum problematum quaestio oritur, an possibile sit, ad tempus aliquid datum, invenire distributionem antecedentem ex qua distributio data produceretur per motum liberum caloris. Si hoc fieri potest, inveniendum est maximum temporis intervallum inter distributionem datam et distributionem antecedentem ex qua data derivari potest. Veruntamen distributio data talis esse potest ut intervallum valorem maximum non habere possit. Haec considerationes suggerunt omnes distributiones quae possunt existere in tria genera redigi posse ; sc.

1. Distributiones quae e distributione antecedente produci nequeunt.
2. Distributiones quae produci possunt e distributionibus determinatis existentibus in temporibus datis ante tempus datarum distributionum, intervallis limites certos haud excedentibus…'

In 1852 he published his paper 'On a universal tendency in nature to the dissipation of mechanical energy' [22] in which he formulated the second law of thermodynamics which states that in any conversion of energy from one form to another a proportion of the energy is dissipated in the form of heat.

Kelvin was first and foremost a mathematician and secondly an experimental physicist and practising engineer. He considered mathematics to be the fundamental tool for both disciplines and the essential path to the truth. Reason told him that if the second law of thermodynamics were true, then it must inevitably mean that the Universe had at some time had a beginning and at some time would die in heat death with energy equally distributed everywhere and no energy potential available to do any work. If the universe had a beginning and an end then so must the Earth and the Solar system and it should be possible to find some limiting case conditions that could place bounds on their ages.

In particular, Kelvin was intensely dissatisfied with the principles of uniformitarianism either in the form suggested by Hutton and Playfair or as accepted by Lyell. Thermodynamics proved beyond doubt that the earth could not be ageless and must have a beginning and an end. Life itself could only have been brought into being by a creator, although it was conceivable that life had been created elsewhere and brought to this planet in an advanced form of development [23]. The future of mankind was also in the hands of the creator even though the potential lifetime of the Earth was limited.

Kelvin was extremely tenacious with his theories. Once he had established the principles he continued to develop the ideas, refining the details to accommodate criticisms, but always maintaining the integrity of the central principles. Even his undergraduate essay 'On the Figure of the Earth' was revised and corrected in later years. In large part, it was this re-iteration of his ideas that kept them alive and maintained his influence over the years.

## 4 Geological time

After leaving Cambridge Kelvin went to Paris to study under Henri Victor Regnualt. There he read Fourier's *Analytic Theory of Heat* which contained the equation for diffusion of heat through a solid body. Kelvin had already come across this equation when he was an undergraduate at Glasgow University in 1839 under Professor Nichol in the Natural Philosophy Classes. In 1841, Kelvin responded anonymously to a book by Kelland at Cambridge criticising Fourier's mathematics [24]. Despite Playfair's influence Cambridge had not yet fully accepted the advances on the Continent. Kelvin decided to use the equation to calculate the age of the earth from when it became a solid body, which was the general view of the state of the earth in Kelvin's time. He also specifically stated that he assumed there was no internal heat generation which was also the general belief at the time. Assuming that the earth had a uniform temperature to begin with and now possessed a temperature gradient as a result of cooling he could calculate, using the diffusion equation, the time taken to achieve this gradient.

In 1868, 10 years after the publication of *On the Origin of Species*, Kelvin addressed the Geological Society of Glasgow on the subject of Geological Time [25]. He had addressed the issue several times discussing the possible age of the sun or of the Earth and attacking the principles of Uniformitarianism, but with little reaction from the geological community.

On this occasion, he spoke more forcibly to the geologists, announcing that 'a great reform in geological speculation seems now to have become necessary'. He explained how the geologists of the previous century had tried to bring geology within the physical sciences and to move away from theologically based chronologies. At the same time, the astronomers had been making great steps in the theory of the motions of planetary bodies. However, the theory of the stability of the planetary movements had been misinterpreted and where the original founders of the theories had acknowledged the simplifications that had been made, these caveats were overlooked by the geologists who adopted the theories. The geologists had tried to use the stability of the heavens to suppose that the universe, including the earth, was essentially unchanging, thus leading to Playfair's statement 'we can discern neither a beginning or the end'.

Nothing, proclaims Kelvin, could be further from the truth. The theorem of the French mathematicians regarding the motions of heavenly bodies, he explains, is a theorem of approximate application and neglects frictional resistance of every kind.

Having established the foundations of his arguments, Kelvin then proceeded to take a quotation from Playfair as his text and to counter the arguments contained within it from two different approaches. He considered firstly the motions of the heavenly bodies including the Earth and secondly the phenomena presented by the earth's crust.

The arguments which he presents are based on a number of earlier papers and lectures extending back to an essay of 85 pages written when he was 16 'On the Figure of the Earth'. That essay was in four parts, Physical Theory, Disturbance in the Moon's Action, Geodetic Measures and Pendulum Observations. While it drew on the work of Airy, Poisson, Pentecoulant, Pratt and Laplace, it was a remarkable work in its own right extending its arguments to cases not considered by the earlier workers. Kelvin kept the manuscript and added amendments to it in 1844, 1866 and 1907; just 2 months before his death he was still returning to this boyhood study.

The 1866 amendments coincide with Kelvin's delivery of the Rede lecture after receiving an honorary doctorate of Laws at Cambridge. The full lecture is not recorded and witnesses describe how Kelvin would keep leaving the main topic to expose or discourse upon common fallacies, eventually returning to somewhere near where he had left the main topic of discussion which was the dissipation of energy. This made the lecture very difficult for his listeners to follow and appears to be typical of his approach to lecturing at Glasgow where it was not uncommon for less committed undergraduates to slip out of his lectures once their presence had been recorded, leaving a hard core of more gifted students to delight in following his intellectual wanderings.

An abstract of the Rede lecture was published in the Cambridge Chronicle a few days later and is also reprinted in the *Life of William Thomson* [19]. In the lecture, he not only considered the amount of heat being lost from the sun (7000 horse-power per square foot) some small fraction of which falling upon the earth providing the energy of coal, and growing combustibles and fuel, but also the loss of heat from the earth of 180 million horse-power from the whole surface.

Tidal friction was also considered as giving rise to dissipation of the earth's energy of rotation [26], the ultimate tendency of which would be to make the earth, sun and moon turn like parts of a rigid body. The effect might possibly amount to as much as one or two hundred seconds in a century. However, astronomical clock making was not wonderful and astronomical clocks could only be made to perform two or three times as accurately as a good pocket watch. Therefore, the only means of determining retardation of the earth was by comparison with the moon, which itself was subject to great irregularities. Adams and Delaunay had calculated that the earth had lost on the moon by some ten seconds in the previous hundred years, but it could not be concluded that this was entirely due to tidal retardation. For example, melting snows and ice caps that caused in imperceptible increase in ocean depths of one and a half inches would slow the earth by two tenths of a second per year. Also, while the direct effect of the moon on the tides in the Thames from London Bridge to the Nore is to retard the rotation of the earth, from the Nore to Exmouth and Jersey the effect is to accelerate the rotation. However, the fact that there is loss of energy by fluid friction makes it certain that the sum of the retarding and accelerating forces results in a net retardation.

The lecture ended with three conclusions, the third of which stated:

'within a finite period of time past the earth must have been, and within a finite period of time to come, the earth must again be unfit for the habitation of man as at present constituted, unless operations have been or are to be performed, which are impossible under the laws to which the known operations going on at present in the material world are subject.'

### 4.1. Tidal retardation of the earth

In 'On geological time' [25], Kelvin goes into more detail about tidal processes. The distribution of water over the surface of the earth is not uniform, but it can be represented by a model of the earth with a uniform layer of water which has the same net effect as the actual oceans. This model is referred to as the tidal spheroid. The tides, which occur twice in each day, are caused because the moon attracts the water on the side of the earth nearest to it into a bulge and also attracts the earth itself more than the total mass so that there is a bulge in the water mass on both sides of the planet. If the moon were stationary with respect to the earth then there would be a bulge in the water level directly below the moon and diametrically opposite it. However, since the earth is rotating with respect to the moon and also the moon is rotating about the earth, and since the mass of water cannot respond to the gravitational field of the moon instantaneously, the tidal bulge lags behind the position of the moon and this in itself demonstrates that frictional processes in the movement of the body of water do occur. The lost energy is dissipated in the form of heat as shown by Joule.

Similar arguments apply to solar tidal forces except that the solar tides have a period of 24 hours and the lunar tidal forces have a period slightly longer due to the moon's rotation about the earth. When the lunar and solar tides coincide the tides are higher than average, called spring tides, and when the moon and sun are at right angles the tides are lower, called neap tides. The

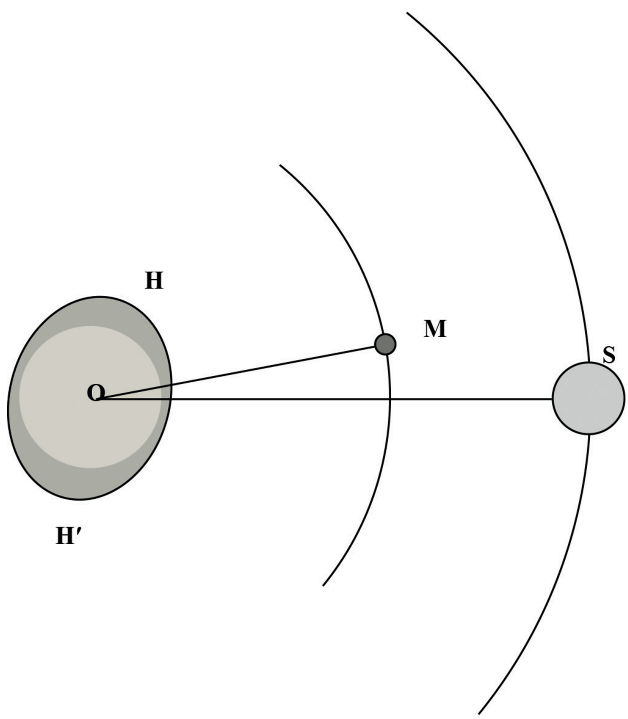


Figure 3: Position of the Sun, Moon and Earth at Spring Tides.

detailed processes are more complex due to tidal streams and in some areas the tides are exceptionally high due to the tidal timing matching a resonance in the local tidal flows.

Since it is clear that energy is being dissipated, and that the primary source of this energy is due to the relative motions of the earth, moon and sun, then the ultimate result of the dissipation of this energy must eventually lead to a static situation in which the relative motions reduce to zero, the moon rotating about the earth in exactly 1 day and with the earth and moon perpetually showing the same sides to one another. Similarly, the Earth–moon complex would show just one face perpetually towards the sun and the three bodies would rotate as a single rigid complex with no tidal forces being exerted on the oceans. The two bulges would stay in the same location forever. To achieve this state, it is clear that the rotation of the earth must be decreasing, and the angular momentum of the moon must be increasing, the orbital distance of the moon also increasing.

To consider this more analytically, consider the situation in Fig. 3 which shows the relative positions of the earth, moon and sun and the tidal bulge at the time of spring tides, viewed from the north. If there were no tidal friction then OMS would be in a straight line and HH´ would be perpendicular to it. But from observation the spring tides are late by between a day and half to three days after the new moon and the full moon. The line OM is therefore inclined forward from OS by the distance that the moon would move in the time of the spring tide lag – for a lag of 12 hours this would be 6°.

Now, the waters of the earth are drawn along with the motion of the earth by friction on the bottom and by friction of water on water and the overall effect is as if the earth and water were rotating within a friction strap. The forces on this friction strap would amount to the weight of two million tons according to the calculations taken from the Rede lecture. This supposes the axis HH´ to be inclined to OM at an angle of 45°, the position which would result in the greatest amount of retardation. If the angle HOM were between 45° and 84° the frictional resistance would be between this amount and one fifth of it. But if the lateness of the spring tides is at least 12 hours, then the angle MOS cannot be less than 6° and the angle HOS is certainly something short of 90°. Therefore, the average spheroidal tide must be less than 1⅛ feet or the amount of resistance to the earth's rotation must exceed one fifth of the estimated superior limit.

The general tendency of the action is therefore to diminish the velocity of the earth's rotation and to lengthen the duration of the day. Similarly, the waters exert a force on the moon forwards in her orbit which has the effect of making the moon's motion slower and to increase her distance from the earth. If the moon were a viscous mass, then she would also feel enormous tidal effects which would tend to slow her rate of rotation until she ended up with one face turned permanently towards the earth, as is indeed the case, and we may therefore suppose it likely that the moon was once a liquid mass.

It is all very well to show that these processes occur in principle, but it is quite another to be able to quantify them especially give the very poor quality of astronomical clocks. There were also arguments to show that the rotation of the earth had not changed by one ten millionth part of twenty four hours since 721BC based on observations of eclipses in 721 BC and 313 BC in Babylon. Dunthorne [27] had used these observations to confirm a suspicion of Halley, that the moon's mean angular motion had been accelerated relative to the earth by 20 seconds of angular velocity/century per century. Laplace, however, while accepting this conclusion, had explained it by showing that the planets indirectly cause an acceleration of the moon's angular velocity through their influence in producing a secular diminution of the eccentricity of the earth's orbit. Calculating out this effect tallied precisely with the supposition that the earth's velocity of rotation had been constant since 721BC.

But, in 1853, Adams – a great English physical astronomer – pointed out an error in Laplace's process, in that he had omitted to take into account the tangential component of the sun's disturbing force on the moon and reworked the problem with this correction. He found that there was an unaccounted for gain of 11.4 seconds of arc per century in the angular velocity of the moon's motion, and Delaunay in France soon confirmed this result, suggesting that the discrepancy could be due to a diminution in the earth's rotational velocity by tidal friction. Adams, Kelvin and Tait then used this hypothesis with certain assumptions as to the proportion of retardations due to the moon and the sun, to show that the earth would get 22 seconds of time behind a thoroughly perfect clock after a century. This in itself discredits Playfair's statement that there is nothing in the motions of the heavenly bodies that tends to their own dissolution or to a permanent alteration of the existing state of things.

If we consider the effect of centrifugal force on the earth a hundred million years ago, then this would be some 3% greater than at present and if the earth had consolidated at this time, under those conditions then it might easily be of the form we observe. However, if we go back in time as much as one thousand million years, then the speed of rotation would have been more than twice as fast as at present and if it solidified then it would be very different in form from that which we observe.

At the very least, whether the earth's lost time is 22 seconds or considerably more or less than 22 seconds, it is evident that there must be a progress of events towards a state infinitely different from the present.

## 4.2 The sun's heat

Next, Kelvin went on to consider the question of the sun's heat, for if Playfair considered planetary motions to be unchanging then it would be necessary to consider also the source of the sun's heat. This might be considered a miraculous body, created by a Creative Power and so designed as to produce unending, constant supplies of heat in violation of those laws of action between matter and matter which we are allowed to investigate on the earth. But, he says, we also know that the Creative Power has created in our minds a wish to investigate and a capacity for investigating; and there is nothing too rash, there is nothing audacious in questioning human assumptions regarding Creative Power. Indeed the very geologists who support Playfair are strenuous in insisting that we must consider the laws observable in the present state of things as perennial laws.

He then considered all the energy that would be released by the planets falling into the sun. Jupiter alone would provide 32,240 years of the sun's heat and all together would provide some 46,000 year's heat. Given that, it is accepted that the sun has already, in geological periods, emitted maybe a thousand times as much heat as would be produced by all the planets falling together into the sun. But Playfair and his followers take no consideration of this prodigious dissipation of energy.

### *4.2.1 Meteoric theory*

In 1854, Kelvin considered three possible sources of the sun's heat [28]: firstly, that the sun has only primeval heat and is cooling as a result of the dissipation of this heat; secondly that the sun is 'burning' and generating heat through chemical processes; and finally that the sun acquires its heat from the energy provided by meteors falling into it and releasing their kinetic energy in the form of heat. The first of these possibilities he had previously shown to be entirely untenable since, unless the sun's thermal conductivity was enormously greater than any terrestrial matter the sun would become dark in a matter of minutes, or days, or at best a few years at the present rate of emission.

Next, he considered the meteoric theory proposed by Mayer and by Waterston. The fact that there are meteors arriving at the earth shows that there must always be meteors falling into the sun, and since Joule had shown the enormous quantities of heat generated from a meteor's motion relative to the earth in his explanation of falling stars, it follows that some of the sun's heat must be due to meteors.

According to Pouillet, the amount of heat incident per second on a square foot at the earth's surface is 0.06 of a thermal unit (pound-water-degree) centigrade. Since the distance from the earth to the sun is 95,000,000 miles and the sun's radius is 441,000 miles, the rate of emission of heat from the sun must be:

$0.06 \times (95{,}000{,}000/441{,}000)^2 = 2781$ thermal units/second/square foot of his surface, which is equivalent to 3,869,000 ft lb-weight/sec/sq ft.

Neglecting atmospheric resistance and the mile and a quarter per second speed of rotation of the sun's surface, the impact speed of a meteor would be that obtained by falling from an infinite distance, which is that obtained by the action of a constant force equal to its weight at the sun's surface, operating through a space equal to his radius. The force of gravity at the sun's surface being about 28 times that at the earth's surface, the speed is

$$\sqrt{\frac{2\times 28\times 32.2\times 441{,}000}{5280}} = 390 \text{ miles per second}$$

And the mechanical value per pound of meteoric matter is

$$28\times 441{,}000\times 5280 = 65{,}000{,}000{,}000 \text{ ft lb-weight}$$

Hence, the amount of meteoric matter required to account for the sun's heat would be 0.000060 pounds per second, or about one pound per square foot every five hours. If this density of meteors were falling into the sun, whether on linear, parabolic or hyperbolic paths, we would find that the earth was intercepting far more of them than is actually the case. It, therefore, follows that the majority of these meteorites are orbiting the sun inside the orbit of the earth and Kelvin suggests that it is these bodies which form the zodiacal light, the outer edge of which appears to reach nearly to the earth [29]. In this case, the meteors would approach the sun on a gradual spiral path with a speed little more than that of a circular orbiting body. The speed lost by a meteor in this case is $1/\sqrt{2}$ of that due to gravitation from an infinite distance or 276 miles per second and, therefore, the mass of meteorites required is roughly double the previous estimate. The whole surface of the sun would, therefore, be covered to a depth of 60 feet in a year and the diameter of the sun would increase by 1 mile in 88 years. In 40,000 years the [angular] diameter would grow by only 1 second of arc which would be undetectable without the aid of powerful telescopes.

Finally, he considers what chemical actions would be required to produce heat at a rate of 7000 horse-power per square foot. This would require 1500 lbs of coal to be burnt per hour, but it would not be possible to provide oxygen to keep the fire burning at a sufficient rate. Therefore the action must be more like gunpowder which does not require an externally provided accelerant. He assumes that the heat of combustion could not be much more than 4000 thermal units per pound of matter – the greatest thermal reaction known being somewhat less than that. But the sun loses 2781 thermal units per second for each square foot implying a loss of about 0.7 of a pound of matter per square foot per second. At this rate, the sun would lose about 0.5 feet of thickness in a minute or 55 miles in a year. At the same rate, a mass the size of the sun would burn away in 8000 years, so it can be concluded that the sun does not get its energy by chemical action.

### *4.2.2 The sun as a cooling body*

In 1862 Kelvin addressed this subject again [30,31], pointing out that the amount of zodiacal matter would have to amount to at least 1/5000th of the mass of the sun, and that this would be expected to have some noticeable effect on the orbits of the planets. Indeed, some such variations had been found by M. le Verrier in his observations of Mercury [32], but the amount of matter indicated was far too small. The mass of material would need to be very close to the sun indeed and the density would then be such that comets passing this close would be perceptibly slowed. He concluded that the meteoric theory was, therefore, unlikely and since no chemical theory was tenable he re-addressed the problems of treating the sun as a cooling body. The considerations here are complicated by the fact that the interior of the sun must be at very high pressure and density and that it is not reliably known how matter behaves under these conditions, but on the basis that the sun's specific heat is more than ten times and less than 10,000 times that of liquid water, then the temperature must sink by 100°C in sometime between 700 and 7000 years. He then attacks Darwin's estimate of 300 Ma for the denudation of the Weald [17] on the basis of whether it is more credible to assume that the conditions of the sun's matter differ 1000 times more than dynamics compel us to suppose, or that a stormy sea and channel tides of extreme violence should encroach on a chalk cliff 1000 times more rapidly than Darwin's estimate of one inch per century.

Finally, he considers what the source of the sun's heat could have been, if not by the act of a creative power. He concludes that this must have been by meteoric accretion and that this theory would have no difficulty in accounting for 20,000,000 years of heat, and that the age of the sun is probably not more than 100 Ma and almost certainly not more than 500 Ma.

## 4.3 Cooling of the Earth

Thirdly, Kelvin considered the question of the underground heat of the earth, to see whether this might provide justification for Playfair's assertion that the phenomena presented all through its crust gave no evidence of a beginning and no progress or advance towards an end. The argument is based on the observation that if you bore into the earth it is warm, and the deeper you go the warmer it gets. He admits that some geologists acknowledge that there may be such a temperature gradient in some places, but claim that this is not sufficient to suppose that it is true everywhere. Kelvin had long advocated, and now reiterated his suggestions, that there should be a global survey of underground temperatures in widely varying locations. In fact, at a recent meeting of the British Association (BA) at Dundee, a committee had been established for investigating underground temperature.

The determination of the age of the earth from knowledge of the existing temperature gradient, and the surface temperature is mathematically feasible but relies on a number of assumptions about the condition of the earth which were well recognised by Kelvin. The thermal conductivity of rock had been established by observation at a number of locations and the variations due to daily, annual and semi-annual changes in the surface temperature had been well observed by a number of people including Fourier. Secondly, the nature of the interior of the earth needed consideration and Kelvin worked on the basis that the earth was essentially a homogeneous ball of consolidated rock that was cooling from an initial temperature of around 7000°F. In 'On geological time' he did not go into the details of these calculations as they had been discussed in great depth in his earlier papers 'On the secular cooling of the earth' [8] and 'On the rigidity of the earth' [33].

Secular cooling was a most detailed and reasoned analysis of the earth considered as a cooling body. The exposition is based on Fourier's mathematical theory of the conduction of heat and its essential prerequisite that there was an initial state prior to which the cooling functions are divergent, and which therefore must have been arrived at through some other mechanism. Kelvin had established the criterion for such an initial distribution in the *Cambridge Mathematical Journal* some 19 years previously and had outlined the application of Fourier's theory to the cooling earth in his inaugural dissertation.

An essential factor in applying the cooling solution is to determine the average rate of increase in temperature with depth and, as noted above, Kelvin had called repeatedly for global geothermic surveys to be carried out so that this figure could be determined with a reasonable degree of certainty. For the time being he had to use the average of data from three different locations, in which gave a rate of 1°F for every 50 feet of depth. This temperature gradient can only result from a continual loss of heat from the surface of the earth and must be supplied either from an initial store of heat or from some form of chemical action. In either case, the source of the heat must be limited. Kelvin dismisses the suggestions of Lyell that the chemical sources might be regenerated by electrolytic action as being fundamentally opposed to the second law of thermodynamics.

He next considers the suggestion of Poisson that the present underground heat was the result of the earth having passed through hotter stellar regions at some time in its past. Kelvin calculated, using values of thermal capacity for the earth's crust obtained from Forbes' measurements in Edinburgh, that if such a transit had taken place between 1250 and 5000 years previously the region of space must have been 25–50°F above the present surface temperature of the earth in order to account for the observed temperature gradient. However, no historical record indicates that such an event had occurred within this time scale. But if the heating had occurred as much as 20,000 years ago, then the temperature must have been 100°F more than at present which would have been fatal to life. The further back such an event had happened, the hotter it must have been, until at 200 Ma ago the temperature would have been 10,000°F which is a somewhat high estimate of the temperature of melting rock. The more acceptable figure of 7,000°F would have occurred some 95 Ma ago.

These estimates were based on Fourier's solution for the problem of finding the rate of variation of temperature from point to point, and the actual temperature at any point in an infinite solid given as an initial condition that the temperature had two different values on the two sides of an infinite plane. The solution is

$$\frac{dv}{dx} = \frac{V}{\sqrt{\pi kt}} e^{-\frac{x^2}{4kt}} \tag{1}$$

$$v = v_0 + \frac{2V}{\sqrt{\pi}} \int_0^{\frac{x}{2\sqrt{kt}}} dz e^{-z^2} \tag{2}$$

where

$k$ denotes the thermal conductivity of the solid, measured in terms of the thermal capacity of the unit of bulk, $V$ the half the difference of the two initial temperatures, $v_0$ their arithmetical mean, $t$ the time,

$x$ the distance of any point from the middle plane,

$v$ the temperature of the point $x$ at time $t$, and $\frac{dv}{dx}$ the rate of variation of the temperature per unit length perpendicular to the isothermal plane.

Kelvin demonstrates the solution by verifying

1. That the expression for satisfies Fourier's equation for heat:

   $$\frac{dv}{dt} = k\frac{d^2v}{dx^2}$$

2. That when $t = 0$, the expression for $v$ becomes $v_0 + V$ for all positive, and $v_0 - V$ for all negative values of $x$.

3. That the expression for is the differential coefficient of the expression with reference to.

(1) and (3) being proved directly by differentiation, and (2) by showing that when and is positive:

$$v = v_0 + \frac{2V}{\sqrt{\pi}} \int_0^{\infty} dz e^{-z^2} \tag{3}$$

And since the known value of the integral is : $\frac{1}{2}\sqrt{\pi}$

$$v = v_0 - V$$

And, for all values of the second term has equal positive and negative values for equal positive and negative values of, so that when $t = 0$ and $x$ is negative:

$$v = v_0 + V$$

These results are expressed graphically in Fig. 4 reproduced from [8], which shows the temperature as a function of the distance from the surface and the rate of increase in temperature with depth. It can be shown that this is without significant error for a solid sphere, initially heated to a uniform temperature and suddenly having its surface reduced to some other constant temperature, which is maintained thereafter. For a globe with a diameter of 8000 miles, the error will not be significant for more than 1000 Ma since the variation in temperature is insignificant below a depth of 568 miles and therefore the surface may be well considered as a plane surface.

To use the diagram to show the variation, which would now exist if the initial temperature drop had occurred 100 Ma ago, with a temperature reduction at the surface of V °F, then on the scale of depth below the surface OX, length 'a' represents 400,000 ft.

For the rate of increase of temperature with depth, length 'b' on the scale parallel to OY represents 1/354,000 of $V$ per foot, so that if $V$ =7000°F 'b' will represent 1/50°F per foot.

For the excess of temperature above that at the surface, length 'b' on the scale parallel to OY represents or $V \,/\, \tfrac{1}{2}\sqrt{\pi}$ 7900°F when $V$ =7000°F.

It can be seen that while the rate of increase in temperature with depth is around 1/50°F per foot for the first 100,000 feet or so, after that the rate decreases dramatically and at 800,000 feet would be 1/50 of that value. Below a depth of about 100 miles the temperature of the earth, whether liquid or solid, would essentially be the proper melting temperature at that depth.

Kelvin addressed directly two major arguments against this theory (1) that the earth was once all melted, or at least the surface layers were all melted and that it was never a uniform 7000°F throughout its mass; and (2) that no natural action could have instantaneously reduced the surface temperature by some 7000°F and then maintained that condition thereafter. For the latter objection, he argued that whatever the initial condition, the surface would have cooled quite rapidly, over a period of weeks or months or years, to establish a solid crust which with a surface temperature not vastly different from that at present.

With regard to the former argument, he pointed out that it is difficult to establish the precise nature of the body of the earth or the process of its solidification without more detailed knowledge of the thermal conductivity and the heat capacity of the rock. The earth may have started as a completely liquid mass, or as a solid cold core which was then heated by the impact of meteorites resulting in a solid cooler core surrounded by a molten layer. The model behaves differently depending on whether the rock shrinks on cooling, or, as is the case with water, it expands. In the former case the temperature will increase with pressure and depth, and in the latter the temperature at higher pressures and depths will be lower than near the surface. In this case, solidification will occur from the centre outwards to result in a solid mass. In the former case, the surface would first solidify, but would break up due to buckling and shrinkage and the solid portions would sink through the underlying liquid. This process would continue resulting in a honeycomb structure of solid masses interspersed with liquid rock. Kelvin accepted

Bischof's findings that melted granite, slate and trachyte all contracted by about 20% on freezing, justifying the use of this model.

However, many geologists still supported a model of the earth that comprised a liquid core supporting a thin solid crust and Kelvin addressed this directly in 1862 [33], when he considered the effects the rigidity of the earth on the solar semiannual and lunar fortnightly nutations and he was able to demonstrate that the earth must be at least as rigid as glass, and probably much more so. He also returned to the subject in 1872 [34] and 1876 [35].

All of these ideas were brought together in the paper he presented to the Glasgow geological society [25] in order to support his cry that 'A great reform in geological speculation seems now to have become necessary'. Taking all these considerations into account, he concluded that some upper bound must be placed on the age of the earth, whether it be 50, 100 or 300 Ma, but in any case it was clear that the earth could not be older than 1000 Ma. Most likely he said was that the age of the earth was some such period as 100 Ma.

The strength of this attack could not be allowed to go unchallenged. In 1869, Thomas Henry Huxley (Fig. 5) made his presidential address to the Geological Society [9] and made use of the opportunity to refute Kelvin's arguments. He is often cited as rejecting Kelvin's estimates in defence of Darwin's theory of natural selection. However, although he was convinced by the arguments for evolution, and the progressive development of species, he was not totally convinced that natural selection was the process by which this was achieved. He was quite firm in the statement in his address that Biology had to take its time from Geology and adapt its theories to fit with the time scales that were available from geological principles.

Neither did he particularly refute the age estimates that Kelvin had produced – indeed, his own estimates of the age of the Earth based on sedimentation rates agreed on a figure around 100 Ma. He did take grave exception to the suggestions from Kelvin that Geologists were fundamentally wrong in their approaches to the subject.

$$ON = x \qquad a = 2\sqrt{kt}$$

$$NP' = be^{-x^2/a^2} = y' \qquad \frac{dv}{dx} = \frac{V}{a} \cdot \frac{NP}{b\frac{1}{2}\sqrt{\pi}}$$

$$NP = ONP'A \div a = \frac{1}{a}\int_0^x y'dx \qquad v - v_0 = V \cdot \frac{NP}{b\frac{1}{2}\sqrt{\pi}}$$

The curve OPQ shows excess of temperature above that of the surface.

The curve AP'R shows rate of augmentation of temperature downwards.

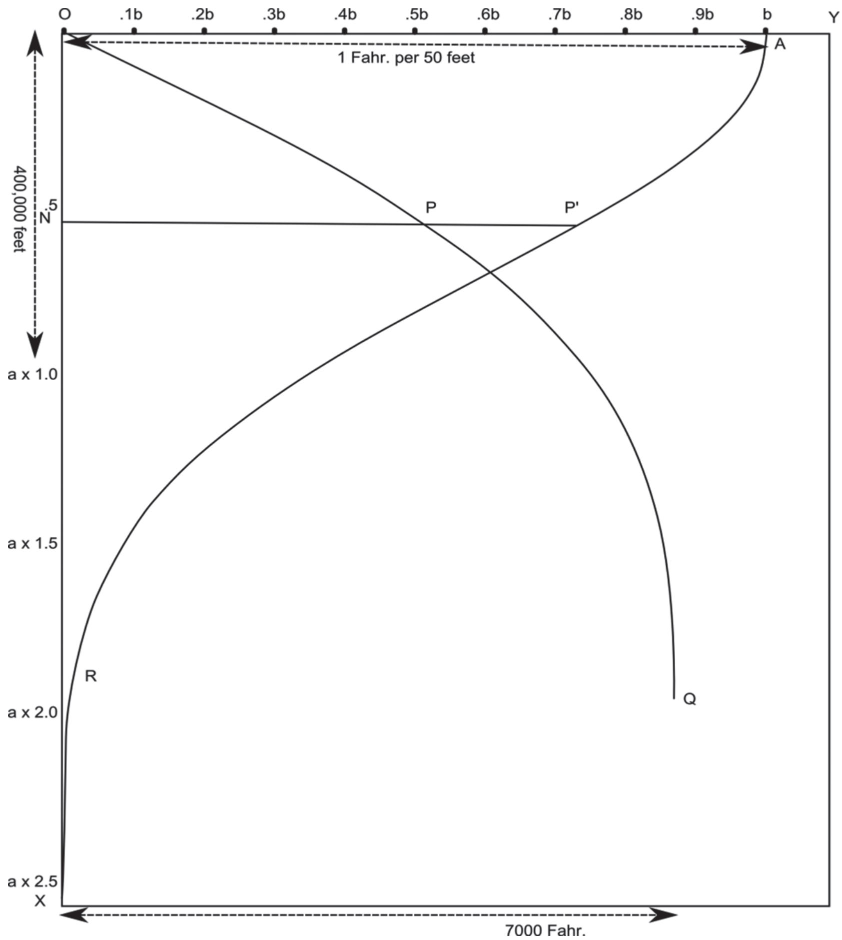


Figure 4: Increase of temperature downwards in the earth (redrawn from [29])

It is obviously Uniformitarianism which the distinguished physicist takes to be the representative of geological speculation in general. And thus a first issue is raised, inasmuch as many persons (and those not the least thoughtful among the younger geologists) do not accept strict Uniformitarianism as the final form of geological speculation. We should say, if Hutton and Playfair declare the course of the world to have been always the same, point out the fallacy by all means, but in so doing do not imagine that you are proving modern geology to be in opposition to natural philosophy. I do not suppose that, at the present day, any geologist would be found to maintain absolute Uniformitarianism, to deny that the rapidity of the rotation of the earth may be diminishing, that the sun may be waxing dim, or that the earth itself may be cooling. Most of us, I suspect, are Gallios, "who care for none of these things," being of opinion that, true or fictitious, they have made no practical difference to the earth, during the period of which a record is preserved in stratified deposits.

The accusation that we have been running counter to the principles of natural philosophy, therefore, is devoid of foundation. The only question which can arise is whether we have, or have not, been tacitly making assumptions which are in opposition to certain conclusions which

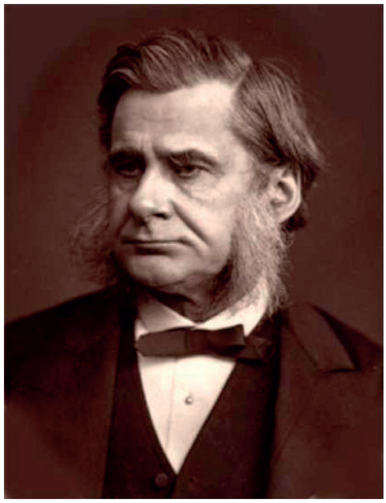

Figure 5: Thomas Henry Huxley.

may be drawn from those principles. And this question subdivides itself into two:–the first, are we really contravening such conclusions? the second, if we are, are those conclusions so firmly based that we may not contravene them? I reply in the negative to both these questions, and I will give you my reasons for so doing. Sir William Thomson believes that he is able to prove by physical reasonings, "that the existing state of things on the earth, life on the earth–all geological history showing continuity of life–must be limited within some such period of time as one hundred million years" [sic].

The first inquiry which arises plainly is, has it ever been denied that this period may be enough for the purposes of geology?'

He also examined Kelvin's assumptions and shows that in all three of his approaches there is lack of precise data and that slight changes in the assumed values could lead to wide variations in the estimates of the Earth's age.

'I do not presume to throw the slightest doubt upon the accuracy of any of the calculations made by such distinguished mathematicians as those who have made the suggestions I have cited. On the contrary, it is necessary to my argument to assume that they are all correct. But I desire to point out that this seems to be one of the many cases in which the admitted accuracy of mathematical processes is allowed to throw a wholly inadmissible appearance of authority over the results obtained by them. Mathematics may be compared to a mill of exquisite workmanship, which grinds you stuff of any degree of fineness; but, nevertheless, what you get out depends on what you put in; and as the grandest mill in the world will not extract wheat-flour from peascods, so pages of formulæ will not get a definite result out of loose data.'

At this point, there is little disagreement, and in his second and subsequent editions of *On the Origin of Species* Darwin withdrew his estimates of the age of the Weald – although he did leave in place his generic statements that there was plenty of time available in which evolution could take place.

Huxley's views about the early history and the formation of the Earth were based on the works of Kant, who had described in great detail how the planets and the Sun could coalesce out of clouds of dust, showing through basic Newtonian principles how the planets obtained their spins and their respective positions in the solar system [13]. He also showed how celestial bodies could go on to collapse so far that the immense pressures and temperatures resulting from the collapse would lead to their eventual explosion producing a new cosmic dust cloud from which new planets could then be built. Kant's exposition was extremely prescient, even suggesting that the universe was full of millions of galaxies and that stars were not confined to the Milky Way. However, his arguments were susceptible to many criticisms in the light of classical physics and chemistry, and it is only recently that we have been discovering just how galaxies and planetary systems are formed and how they eventually die. In particular, his cyclic views were quite unacceptable to strict thermodynamicists who could look ahead to the eventual heat death of the universe, and who could not see where the immeasurable quantities of energy required could possibly come from.

Kelvin himself responded critically to Huxley's paper and shortly afterwards P.G. Tait, a colleague and friend of Kelvin, writing anonymously made a vigorous attack, quoting lengthy passages out of context and completely missing the essential points that Huxley was trying to make [36].

Kelvin's response, while no less vigorous, was more closely reasoned in a paper of three parts entitled 'On Geological Dynamics' [37]. The first part was a direct response to Huxley's address, while the second and third parts addressed the questions of the origin and total amount of Plutonic energy, and a note on the meteoric theory of the sun's heat. In the first part, he re-affirms that in his paper of 1868 he was not desiring a reform of all of geology, but explicitly the principle of Uniformitarianism. Where Huxley had suggested that 'Most of us, I suspect, are Gallios, "who care for none of these things," being of the opinion that, true or fictitious, they have made no practical difference to the earth during the period of which a record is preserved in stratified deposits', Kelvin ripostes that precisely for this reason it is important that evidence for opposing opinions should be thoroughly sifted and not merely disposed as matters of opinion, or 'of faith beyond the realm of reason.' He expresses considerable satisfaction that Huxley should find his estimates of the age of the earth acceptable to geologists, and concludes by asserting that experimental and mathematical investigations of underground temperature should be an integral part of geology, and that he himself should not be regarded 'as a mere passer-by but as one constantly interested in their grand subject and anxious in any way, however slight, to assist them in their search for truth.'

Unlike the rather longer rebuttal by Tait, this response by Kelvin shows the regard and friendliness between Kelvin and Huxley which is often overlooked. Indeed, Kelvin invited Huxley to accompany him on a summer cruise on his yacht, the *Lalla Rookh*, along with Tait, Helmholtz and Tyndall, although it is regrettable that such an intellectually stimulating summer holiday failed to materialise.

Despite Kelvin having stated that uniformitarianism violated the second law of thermodynamics, some geologists and biologists continued to support uniformitarianism and other ideas that violated the second law to the end of the nineteenth century and indeed used these unsupportable ideas to reject Kelvin's criticisms, for example, by suggesting continuous creation of energy in the sun to provide the energy for uniformitarianism. Not only did they not understand the thermodynamic concepts involved in Kelvin's work but they did not see the relevance to their work of a law derived from mechanics (a subject looked down upon in those days).

In the middle of the nineteenth century, the geologists started to quantify the dating of rocks more precisely. The most significant attempt was made by James Croll (1821–1890) who did not regard himself as a geologist. He was the Keeper of the modest Andersonian Museum in Glasgow and during his tenure became a self-taught physicist with a particular interest in glaciation. He also studied astronomy in relation to this topic.

Croll supported the physicists', in particular Kelvin's opposition to uniformitarianism and Kelvin's upper limit of 100 Ma for the age of the earth, and he put forward reasons for accepting this value. He could not, therefore, accept 20 Ma for the age of the sun and so he put forward a theory that would give a higher value but could not provide data to quantify it [38]. He also rejected the estimate of the earth's age calculated from tidal retardation [39] as the equatorial bulge at the time of the earth's solidification would have been eroded over time and be quite different from the existing shape. Assuming a constant shape throughout would lead to an erroneous result. He set about developing a quite different method.

Croll hypothesised that the shape of the earth's orbit around the sun varies slowly with time because of the gravitational influence of all bodies in the solar system [40]. This problem is not solvable analytically (the n-body problem) but he assumed that the orbit varies from near circularity as at present to greatest ellipticity in which configuration the relative lengths of the seasons are different. The hemisphere experiencing winter at aphelion, the remotest part of the orbit, would suffer long hard winters and would not fully recover in the short summer. Reinforcing this difference would be the gradual accumulation of snow and ice. By contrast, the other hemisphere would enjoy a moderate climate with long pleasant summers and short mild winters. Other climatic changes would occur such as shifts in the winds and in tropical currents away from the cold regions and increased precipitation in the cold regions. The snow and ice would reflect the sun's heat and dense fogs would shield the cold regions from solar radiation and eventually an ice age would occur. Arising from the precession of the equinoxes the extremes in climate would alternate from one hemisphere to the other every 10,500 years.

By 1867, Croll had begun to gather data to substantiate his theory. He calculated orbital eccentricities for the last million years and found three periods of extremely high eccentricity between 950,000 and 750,000 years ago. He also found several periods of slightly less eccentricity at later times, the most recent being 100,000 and 200,000 years ago. He then had to decide which of these many periods corresponded to the ice age currently being investigated by geologists. He initially looked at the most recent period of extreme eccentricity around 750,000 years ago but concluded that there would be no trace of glaciation by now. In addition, Lyell had calculated that if the last ice age occurred 850,000 years ago the date of the Cambrian period must extend back nearly 240 Ma, much longer than 100 Ma which Croll had come to accept. If, however, Croll chose the most recent period of relatively extreme eccentricity which ended 8,000 years ago and made certain changes to Lyell's calculation, he reduced the Cambrian period to 60 Ma and hence an age of the earth that corresponded approximately to his preferred value, thus getting agreement between geology and physics. He published his findings in 1868. It is obvious, however, that the age of the earth deduced by this means is very dependent on the degree of eccentricity and on what date is chosen for the ice age, remains of which can still be seen. Lyell's choice is closer to the middle of the last ice age and would have been a better choice for Croll if he had not allowed the 100 Ma estimate by Kelvin to influence his choice. Kelvin seems to have ignored Croll's work perhaps because of its several unsupported assumptions.

Numerous estimates of the age of the Earth were produced using various techniques during the late nineteenth and early twentieth centuries and Dalrymple [3] conveniently tabulates these for us. Between 1860 and 1917, he lists 32 estimates based on the rates of sedimentation or erosion, varying between 3 and 15,000 Ma, but with nearly half of them falling in the range of 50–500 Ma for the period of time since the Cambrian era. Estimates on the basis of orbital physics ranged from Tait's <10 Ma to Kelvin's <1000 Ma (although Jeffreys, on the basis of the eccentricity of the orbit of Mercury suggested the higher figure of 3,000 Ma in 1918 [41]). Estimates based on ocean chemistry such as sodium, chloride or sulphate accumulation up to 1931 produced 12 estimates between 25 Ma and an upper bound of 340 Ma. Cooling of the Earth provided 10 estimates ranging from Tait's low figure of 10–15 Ma to Holmes estimate of >1314 Ma and Haughton's >1280 Ma, but mostly in the range of 20–100 Ma. Solar cooling tended to provide lower estimates from 4.4–5.8 Ma from Ritter in 1899 to Kelvin's 10–500 Ma from 1862.

## 5 Growing opposition

A particularly influential paper with Kelvin was that of Clarence King in 1893, on 'The Age of the Earth' [42], in which he presented temperature distributions calculated for various initial Earth temperatures and cooling times using the same assumptions and mathematics as Kelvin. King's work was based on the assumption of the solidity of the Earth, combined with estimates of the change of the melting point of diabase (a shallow intrusive rock similar in composition to basalt) as a function of depth. These were based on the work of Barus [43,44] who measured changes in volume and latent heat of fusion of diabase as it cooled and solidified from 1500° C. From them, King was able to predict that the change in melting point with temperature amounted to 0.025°C/atmosphere and was linear. The straight line showing this is in Fig. 6.

A consequence was that any reasonable initial temperature for the earth lay on the solid side of the line and therefore the earth was probably never totally molten. Figure 6 shows the variation of temperature with depth, for the earth, for a range of initial assumptions. Those used by Kelvin (curve b) produce a temperature curve which intersects the diabase melting line at two points, implying a molten layer between 42 km and (outside the range of the data plotted) 364 km from the surface, with a solid crust only 42 km thick. Increasing the cooling time to 600 Ma (curve c) avoids the liquid layer but results in a temperature gradient near the surface of only 1°C/68 m – only half the average measured value.

Excluding results that provided near-surface temperature gradients significantly different from the BA's average, and also estimates that required a combination of time and temperature which was more than was absolutely needed, King settled on an a final figure for the age of the earth of 24 Ma (curve e). In 1897, Kelvin presented a paper on 'The Earth as an Abode Fitted for Life' to the Victoria Institute [45] in which he pointed out that changing his initial temperature assumption to only 2000°F – the approximate temperature of lava, would have reduced his 100 Ma estimate to only 10 Ma, and that as a result of refinements in his calculations he would not differ by much from Clarence King's figure of 24 Ma.

While there was still some adherence to the principles of Uniformitarianism among the geological community, most had been content to live with the possibility of an Earth that had been in existence for 100–500Ma. However, the later reductions in the estimates began to conflict with other geological evidence and there was a feeling that the physicists were getting carried away by their theoretical approach with insufficient attention to the fundamental geological principles.

John Perry had been an assistant and occasional collaborator with Kelvin and was well acquainted with Kelvin's approach to the Age of the Earth problem. However, he was not convinced that Kelvin was right in the face of growing discord from the geological community. He had attempted to raise the issue with both Kelvin and Tait but had received no satisfactory response. In 1895 he therefore published his concerns in Nature [46–48] after allowing Kelvin and Tait to see the manuscript beforehand and to provide answers to it in the same edition of Nature.

Perry did not attempt to attack Kelvin's mathematics or procedures, but questioned the basic assumption that the Earth could be modelled as a solid cooling mass. Fisher, in 1881 had shown that the crust could move and changed in height with the advance and retreat of the ice ages [49]. A molten interior to the Earth would allow convection processes as well as conduction, and a honeycomb model would need Kelvin's estimates to be increased 56-fold, bringing them close to

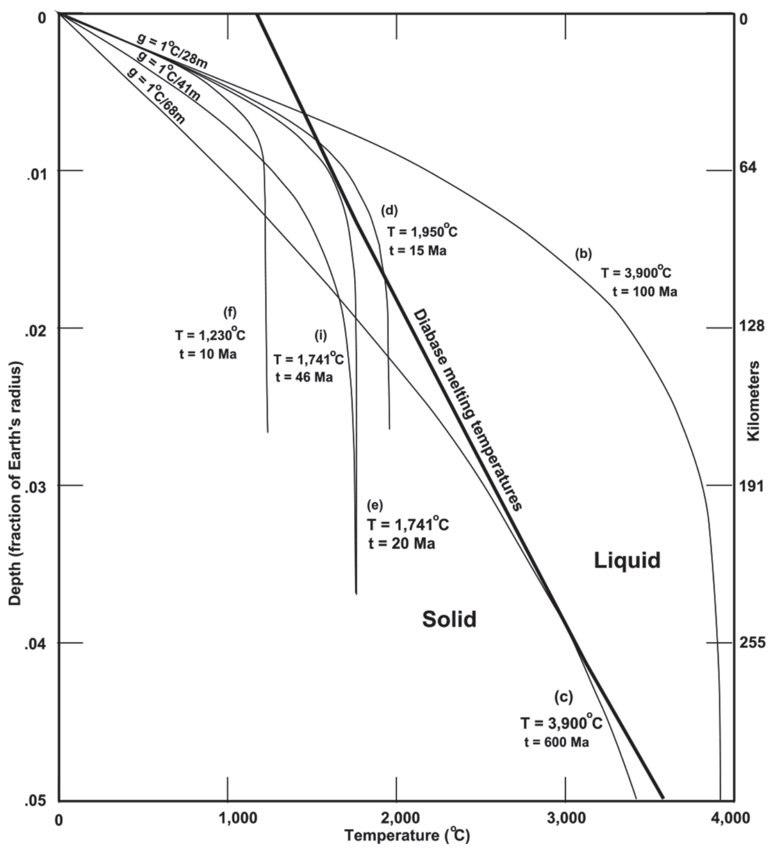


Figure 6: Some of Clarence King's temperature versus depth curves for determining the age of the Earth (adapted from Dalrymple [3, p. 42], after King [42]).

the actual figure of around 4.5 Ga. Perry showed that for a slab of unlimited thickness, initially at uniform temperature – say 4000°C – and with one face thereafter kept at zero temperature, then from the theory of dimensions, if the conductivity is increased $m$ times and all lengths are increased $n$ times, all temperatures remain the same if the times are increased $n^2/m$ times. The gradient at the surface will be altered $n^{-1}$ times, but that can be brought back to an assigned value, with the same value of surface temperature, by altering the conductivity and thickness of an outer surface stratum. In the particular case of a globe, the size of the earth (radius R = $6.38 \times 10^8$ cm) and a conductivity k of 0.47 (79 times that of surface rock), and k/c = 0.165, which is 14 times that of surface rock, where $c$ is the thermal capacity, then, with a shell of rock with a thickness of $4 \times 10^5$ cm (about 2½ miles) superposed, the time of cooling to the present surface gradient of 1 C in 2740 cm would be as much as $98 \times 10^8$ years. With k set to 195 times and k/c to 35 times the value for surface rock, and with a shell 20 miles ($3.272 \times 10^6$ cm), the time would be $127 \times 10^8$ years or 12.7 Ga.

Tait rejected Perry's discussions out of hand, but Kelvin did admit that perhaps he should have placed the upper limit at 4000 Ma instead of 400 Ma. Kelvin accepted the principles of Perry's calculations but did not believe that the model of an earth with a shell of constant thickness and smaller conductivity and thermal capacity was a valid one. Although he welcomed the possibility of determining the change in conductivity and thermal capacity of various rocks at elevated temperatures experimentally, he felt that these assumptions could not be made on the basis of existing data.

Later, on the basis of fresh data on thermal conductivity from Weber and from Barus and Clarence King, and taking into account the augmentation of melting temperature with pressure, Kelvin arrived at a revised estimate of 24 Ma [50] and stated that until there was more knowledge of the augmentation or diminution of thermal conductivity with increasing temperature it would be quite uninteresting to publish any closer estimate.

Perry then wound up the discussion [48] with a full review of the evidence and concluded: 'To sum up, we can find no published record of any lower maximum age of life on the earth as calculated by physicists (I leave out the estimates based upon the assumption of uniform density in the sun, and also those of Mr Clarence King) than 400 million years. From the three physical arguments, Lord Kelvin's higher limits are 1000, 400, and 500 million years. I have shown that we have reasons for believing that the age, from all three, may be very considerably under-estimated. It is to be observed that if we exclude everything but the arguments from mere physics, that the probable age of life on the earth is much less than any of the above estimates; but if the palaeontologists have good reasons for demanding much greater times, I see nothing from the physicist's point of view which denies them four times the greatest of these estimates.'

One reason for Kelvin's obduracy was his over-riding conviction that the possible age of the Sun provided an ultimate limit on the possible age of the Earth. Even this assumption did not go entirely unchallenged, however, and when Thomas Chrowder Chamberlin of the University of Chicago also attacked Kelvin's estimates he made a prophetic statement:

'Is present knowledge relevant to the behaviour of matter under such extraordinary conditions as obtain in the interior of the sun sufficiently exhaustive to warrant the assertion that no unrecognized sources of heat reside there? What the internal composition of the atoms may be is yet an open question. It is not improbable that they are complex organizations and seats of enormous energies. Certainly, no careful chemist would affirm either that the atoms are really elementary or that there may not be locked up in them energies of the first order of magnitude. No cautious chemist would probably venture to assert that the component atomecules, to use a convenient phrase, may not have energies of rotation, revolution, position and be otherwise comparable in kind and proportion to those of a planetary system. Nor would he probably be prepared to affirm or deny that the extraordinary conditions which reside in the centre of the sun may not set free a portion of this energy' [51] [sic].

Darwin had asked his son George, a competent mathematician, to check Kelvin's work but he found no error. The discrepancy must lie in the assumptions, which Kelvin clearly stated as he was accustomed to do, a feature of his work noted by Maxwell. One assumption is the uniformity of the earth in terms of thermal conductivity. It is not an unusual procedure to construct simple models in science in order to obtain an order of magnitude estimate. Taking account of non-uniformity has little effect on the result. The second assumption is that of no internal heat generation. This is 60 years before it was discovered that radioactivity existed and that heat was produced by this fission. Ernest Rutherford (1871–1937) in his famous lecture on radioactivity given at the Royal Institution in 1904 declared that this was the source of the discrepancy. Various attempts were made by Rutherford and his contemporaries to support Rutherford's statement, but these led to conflicting results, mainly because of inadequate data. The omission of internal heat generation is taken by many to be Kelvin's mistake but it was not a mistake because the existence of radioactivity and its heating effect were unknown. However, recent work by England, Molnar and Richter [52], for example, demonstrated that using modern estimates of radioactive heating, whether taken as uniform for simplicity or as it is actually distributed has little effect on Kelvin's answer for the age of the earth, although it has a dominant effect on the age of the sun where the energy arises from nuclear fusion – an effect which was not discovered for another 50 years. When radioactivity was discovered, Kelvin maintained that it could not account for the discrepancy between his estimates of the age of the earth and that required by the geologists and biologists. In this he was right. However, he did not accept the physicists' explanation for the phenomenon and attempted to explain it in mechanical terms just as he and Helmholtz continued to try and find a mechanical theory of electromagnetism.

## 6 Radioactivity as an additional source of heat

Although radioactive heating has been shown to be insufficient to substantially change the estimate of the earth's age, the phenomenon of radioactivity itself possesses the ability to give a measure of time as a consequence of the time it takes for a radioactive element to decay. This decay time is measured by the half-life, that is, the time it takes for half of the radioactive matter to decay. Frederick Soddy (1877–1956) not only observed the heating effect of the release of alpha-particles but discovered isotopes, elements with the same chemical properties but different atomic weights (and hence atomic number). Many of these isotopes are radioactive, for example, there is the very stable uranium 238 isotope and the relatively unstable uranium 235 one. Soddy measured some of these half-lives and also discovered some of the daughter products. Uranium 235 has a half-life of 704 million years (Table 1), which means that half of it decays in that time, three-quarters in twice that time and seven-eighths in thrice that time. The ultimate decay product is the non-radioactive isotope lead 207. Thus, from measured amounts of uranium 235 and lead 207 in a sample of rock, it is possible to calculate the age of the rock. Various elements can be used depending on the composition and age of the rock. In early investigations, the decay product helium was the choice but helium tended to escape from the rock in situ and from the specimens under test in the laboratory and could only supply a lower estimate of the age of the rock. For example, Robert John Strutt, 4th Baron Lord Rayleigh (1875–1947), son of the Nobel prize winner, arrived at 2000 Ma for the age of the earth, an underestimate of the now accepted value but much longer than earlier geological estimates by non-radioactive means.

The person who put the method on a firm foundation was Arthur Holmes (1890–1965) who, from 1913 onwards [53], made careful measurements of half-lives and daughter products of a large number of radioactive elements. It was this method based on his data that established the dates of the oldest rocks and gave a continuous time history for all geological work including fossil dating. A list of geological periods is given in Table 2.

## Conclusions

The conflict among physicists, geologists and evolutionists to reach a consensus on the age of the earth lasted for well over half a century. Two camps were led by towering figures in science. On the one hand, were the physicists led by Lord Kelvin supported by Tait and Helmholtz. All three believed in a mechanical universe and all three were intransigent in their views. On the other side were the geologists and evolutionists led by Sir Charles Lyell aided by Huxley and to a lesser extent Darwin, the first two as equally intransigent as the physicists. Kelvin having conceived, at an early date, methods for calculating the age of the earth did little to develop new methods or to investigate changes to his original assumptions for half a century. Lyell who coined the term uniformitarianism in geology following the work of Hutton and Playfair stuck to the idea for a similar length of time. It was only when other physicists and geologists developed new methods and gathered more information and accepted the truth of the second law of thermodynamics that some semblance of agreement began to emerge. Finally, it was the development of rock dating by radioactive elements that produced general acceptance of the ages of rock and fossils and of the earth itself.

Kelvin and Tait's greatest desire was to overthrow the principle of Uniformitarianism. This theory had originated in the eighteenth century, and in less extreme form had been widely, if often passively, accepted in the geological community by the middle of the nineteenth century. It was largely due to a single text book, and on the basis that reason based on observation seemed to suggest that long periods of time could account most easily for the geological record. But geology was more concerned with sequence than with absolutes and while uniformitarianism was not denounced, absolute time scales were not a necessity. Wherever geologists or astronomers did make attempts at some absolute dating, the results held so many uncertainties that Kelvin's original estimates were never really considered to be unacceptable. Only later, when the estimates started getting lower and lower were they seriously questioned.

Table 1: Half-life value for various elements.

| Element | Decay product | Half-life |
|---|---|---|
| Uranium 235 | Lead 207 | 704 million years |
| Uranium 238 | Lead 206 | 4.5 billion years |
| Carbon 14 | Nitrogen 14 | 5730 rs |

Table 2: Modern classification of geological periods.

| Period | Millions of years ago | Features |
|---|---|---|
| Precambrian | 4500–590 | Oldest rock found so far, 3800 Fossils rare. Earth's crust formed 4500 |
| Cambrian | 590–515 | Abundancy of fossils including primitive representatives of modern invertebrates, trilobites, brachiopods, gastropods |
| Ordovician | 515–445 | Graptolite fossils abundant in deep water. Ice age 500 |
| Silurian | 445–415 | First true fish appearedFirst evidence of plant life |
| Devonian | 415–370 | Invertebrate fossils such as corals, brachiopods, ammonoids, crinoids in marine deposits, old red sandstone |
| Carboniferous | 370–280 | Land plants prolific and led to major coal deposits. Amphibians more prolific. Some reptiles evolve |
| Permian | 280–240 | Ice age 250 |
| Triassic | 240–200 | Dinosaurs appeared |
| Jurassic | 200–135 | Dinosaurs flourished and developed |
| Cretaceous | 135–65 | Dinosaurs died out |
| Tertiary | 65–1.8 | Modern invertebrates and mammals evolved. Flowering plants dominant |
| Quaternary | 1.8–present day | Ice age 1.8 m to 10,000 years. Fossils of horses, pigs, elephants. Man dominant |

Uniformitarianism never quite died completely, and even Einstein considered that even if the life of the Earth was finite the life of the universe as a whole was infinite and he applied a correction factor to his theories to allow this to be true. He was never completely happy with this correction, which later was removed. Even today modern theories suggest a cycle of universe birth, expansion, collapse and eventual re-birth.

The entire debate is an interesting example of the way in which science progresses, with theories proposed by influential figures, rising to prominence with them, and never quite fading away until their proponents also passed away. The conflict sadly detracts from the reputations of Lyell and Kelvin. In particular, Kelvin who was revered as the greatest physicist of the century has in retrospect suffered most. This is partly because he was so far out on the age of the earth and partly because of his attachment to mechanical illustrations and explanations of the topics constituting the basic physics of his time. However, his appreciation of physics as a whole can still inspire those who now attempt to do the same for a subject now of massively greater breadth.

## References

Note: The first six references have been drawn on extensively throughout and where original sources were not available the references are noted as 'cited in' one of these publications although generally the references will have occurred in more than one of these sources. MPP refers to Mathematical and Physical Papers, 6 vols, Cambridge, 1882–1911; PLA refers to Popular Lectures and Addresses, 3 vols., London, 1891–1894; T&T' refers to [54].

[1] Albritton, C.C., *The Abyss of Time*, Dover Publications, Inc.: Mineola, New York, 2002 (Unabridged republication of the edition published by J.P. Tarcher, Los Angeles, 1986).
[2] Burchfield, J.D., *Lord Kelvin and the Age of the Earth*, University of Chicago Press: Chicago and London, 1990 (First published 1975).
[3] Dalrymple, G.B., *The Age of the Earth*, Stanford University Press: California, 1991.
[4] Jackson, P.W., *The Chronologer's Quest*, Cambridge University Press: Cambridge and New York, 2006.
[5] Smith, C. & Wise, M.N., *Energy and Empire – A Biographical Study of Lord Kelvin*, Cambridge University Press: Cambridge, 1989.
[6] Thompson, S.P., *The Life of William Thomson, Baron Kelvin of Largs*, MacMillan and Co.: London, 1910.
[7] Hutton, J., Theory of the Earth; or an investigation of the laws observable in the composition, dissolution, and restoration of land upon the globe. *Transactions of the Royal Society of Edinburgh*, **1(2)**, pp. 209–304, 1788.
[8] Thomson, W., On the secular cooling of the earth. *Transactions of the Royal Society of Edinburgh*, **23**, pp. 157–170, 1864 (paper read 28 April 1862); *Transactions of the Royal Society of Edinburgh*, **XXIII**, pp. 157–170, 1864; *Philosophical Magazine*., **XXV**, pp. 1–14, Jan 1863; *The Edinburgh New Philosophical Journal*, **XVI**, pp. 151–152, 1862; MPP, **III art xciv**, pp. 295–311; T&T', Appendix D.
[9] Huxley, T.H., Anniversary address of the president: geological society. *Quarterly Journal of the Geological Society of London*, **25**, pp. xxxvii–liii, 1869.
[10] Ussher, J., *The Annals of the World. Deduced from the Origin of Time and Continued to the Beginning of the Emperour Vespasian's Reign, and the Total Destruction and Abolition of the Temple and Commonwealth of the Jews*, E. Tyler for J. Crook and G. Bedell: London, 1658 (cited in [3]).
[11] Maillet, B.d., *Telliamed, or Conversations Between and Indian Philosopher and a French Missionary on the Diminution of the Sea*, University of Illinois Press: Urbana, 1968 (Originally published in 1748).
[12] Comte de Buffon, G.-L.L., *Des Epoques de la Nature*, vol. 10, Ser C, Museum National d'Histoire Naturelle: Paris, 1962.
[13] Kant, I., *Universal Natural History and Theory of the Heavens or an Essay on the Constitution and the Mechanical Origin of the Entire Structure of the Universe Based on Newtonian Principles*, Vancouver Island University: Vancouver 1998, revised 2008, 1755 (Based on George Reimer's edition of the Complete Works of Immanuelle Kant, 1905).
[14] Hutton, J., *Theory of the Earth With Proofs and Illustrations*, printed for Cadell and Davies: London; printed for William Creech, Edinburgh, 1795 (cited in [1]).
[15] Playfair, J., *Illustrations of the Huttonian Theory of the Earth*, Caldell and Davies: Edinburgh, 1802 (cited in [1]).
[16] Lyell, C., *Principles of Geology*, John Murray: London, 1830–1833 (cited in [1]).
[17] Darwin, C., *On the Origin of Species*, Harvard University Press: Cambridge, MA and London, England, 1859 (facsimile of the first edition published in 2003).
[18] Darwin, F., *The Life and Letters of Charles Darwin*, vol II, John Murray: London, 1887.
[19] Thompson, S.P., *The Life of William Thomson, Baron Kelvin of Largs*, Chapter 4, The Glasgow Chair, MacMillan and Co. Ltd.: London, pp. 160–189, 1910.
[20] Thomson, W., On the linear motion of heat. *Cambridge Mathematical Journal*, **III**, pp. 170–174, 1842; *Cambridge Mathematical Journal*, **III**, pp. 206–211 1843; MPP, **I art iv**, pp. 10–15; MPP, **I art v**, pp. 16–21.
[21] Thomson, W., Note on some points in the theory of heat. *Cambridge Mathematical Journal*, **IV**, pp. 62–64, 1844; MPP, **I art xi**, pp. 36–38 (including a note added in 1881).

[22] Thomson, W., On a universal tendency in nature to the dissipation of mechanical energy. *Philosophical Magazine Series 4*, **4**, pp. 304–306, 1852.
[23] Thomson, W., Address to the British Association at Edinburgh. *British Association Report*, **XLI**, pp. lxxxiv–cv, 1871; *Nature*, **IV**, pp. 262–270, Aug 3 1871; *American Journal of Science*, **II(3)**, pp. 269–294, 1871; MPP, **II art. lxvi**, pp. 25–27; PLA, **II**, pp. 132–205.
[24] Thomson, W., Note on a passage in Fourier's 'heat. *Cambridge Mathematical Journal*, **III**, pp. 25–27, 1841; MPP, **I art ii**, pp. 7–9.
[25] Thomson, W., On geological time. *Transactions of the Geological Society of Glasgow*, **3(1)**, pp. 1–28, 1871 (paper read Feb 27 1868); PLA, **II**, pp. 10–64.
[26] Thomson, W., Extract 'On the observations and calculations required to find the tidal retardation of the earth's rotation', *The Rede Lecture, Cambridge*, 23 May 1866; PLA, **II**, pp. 65–72; MPP, **III art xcv**, pp. 337–341.
[27] Dunthorne, R., On the acceleration of the moon. *Philosophical Transactions*, **46**, pp. 162–172, 1749.
[28] Thomson, W., On the mechanical action of radiant heat or Light. On the power of animated creatures over matter. On the sources available to man for the production of mechanical effect. *Proceedings of the Royal Society of Edinburgh*, **III**, pp. 108–113, 1857 (Read 2 Feb 1852); MPP, **I art lviii**, pp. 505–510.
[29] Thomson, W., On the mechanical energies of the solar system. *Proceedings of the Royal Society of Edinburgh*, **III**, pp. 241–244, 1854, ; Appendix on the age of the sun added Aug 15 1854; *Proceedings of the Royal Society of Edinburgh*, **XXI**, pp. 63–80, 1857; *Comptes Rendu*, **XXXIX**, pp. 682–687, Oct. 1854; *Philosophical Magazine.* **VIII**, pp. 409–430, Dec 1854; MPP, **II art lxvi**, pp. 1–25.
[30] Thomson, W., On the age of the sun's heat. *Macmillan's Magazine*, pp. 288–393, March 5 1862; PLA, **I**, pp. 349–368.
[31] Thomson, W., Physical considerations regarding the possible age of the sun's heat. *British Association Report*, **pt ii**, pp. 27–28, 1861, *Philosophical Magazine*, **XXIII**, pp. 158–160, Feb 1862; PLA, **I**, pp. 349–368.
[32] Thomson, W., Recent investigations of M. Le Verrier on the motion of mercury. *Proceedings of the Philosophical Society of Glasgow*, **IV**, pp. 263–266, 1859 (Read Dec 14 1859); MPP, **V**, pp. 134–137.
[33] Thomson, W., On the rigidity of the Earth. *Proceedings of the Philosophical Society of Glasgow*, **V**, pp. 169–170, 1862 (Read Mar 26 1862); *Proceeding of the Royal Society London*, **XII**, pp. 103–104, 1862 (Read May 15 1862 – abstract); *Phil. Trans.*, **CLIII**, pp. 573–582, 1863 (appendix added Jan 2 1864); MPP, **III art xcv**, pp. 312–336; *Phil. Mag.*, **XXV**, pp. 149–151, Feb 1863; T&T', pp. 689–704.
[34] Thomson, W., The rigidity of the earth. *Nature*, **V**, pp. 223–224, 18 January 1872.
[35] Thomson, W., Review of the evidence regarding the physical condition of the Earth. *British Association Report*, **pt ii**, pp. 1–12, 1876, Presidential Address to the Mathematical and Physical Science Section of the British Association at Glasgow, 7 September 1876; *Nature*, **XIV**, pp. 138–161, 1876; *American Journal of Science*, **XII**, pp. 336–354, 1876; MPP, **III art xcv**, pp. 320–335; PLA, **II**, pp. 238–272.
[36] Tait, P.G., Geological time. *North British Revolution*, **50**, pp. 215–233, 1869.
[37] Thomson, W., Geological Dynamics. *Transactions of the Geological Society of Glasgow*, **III**, pp. 215–240, 1871 (Read April 5 1869); *Geological Magazine*, **6**, pp. 472–476, 1869; PLA, **II**, pp. 73–127.
[38] Croll, J., On geological time and the probable date of the glacial and upper Miocene period. *Philosophical Magazine*, **Ser 4**, **35**, pp. 363–384, 1868; *Philosophical Magazine*, **Ser 4**, **36**, pp. 362–386, 1868.

[39] Croll, J., On the age of the Earth determined from tidal retardations. *Nature*, **4**, pp. 323–324, Aug 24 1871.
[40] Croll, J., On the eccentricity of the Earth's orbit and its physical relations to the glacial epoch. *Philosophical Magazine*, **Ser 4**, **33**, pp. 119–131, 1867.
[41] Jeffreys, H., On the early history of the solar system. *Monthly Notice of the Royal Astronomical Society*, **78**, pp. 424–441, 1918 (cited in [3]).
[42] King, C., The age of the Earth. *American Journal of Science*, **Ser 3**, **45**, pp. 1–20, 1893, (cited in[3]).
[43] Barus, C., The contraction of molten rock. *American Journal of Science*, **142**, pp. 498–499, 1891.
[44] Barus, C., Criticism of Mr Fisher's remarks on rock fusion. *American Journal of Science*, **146**, pp. 140–141, 1893.
[45] Thomson, W., The age of the Earth as an abode fitted for life. *Philosophical Magazine Series 5*, **47**, pp. 69–90, 1899 (1897 address before the Victoria Institute, with numerous additions written at various times from June 1897 to May 1898).
[46] Perry, J., On the age of the Earth. *Nature*, **51(1314)**, pp. 224–227, 1895.
[47] Perry, J., On the age of the Earth. *Nature*, **51(1319)**, p. 341, 1895.
[48] Perry, J., On the age of the Earth. *Nature*, **51(1329)**, pp. 582–585, 1895.
[49] Fisher, O., On the depression of ice-loaded lands. *Geological Magazine Series 2*,**,** **9**, p. 526, 1882.
[50] Thomson, W., The age of the Earth. *Nature*, **51**, pp. 438–440, 1895.
[51] Chamberlain, T.C., Lord Kelvin's address on the age of the Earth as an abode fitted for life. *Science*, **9**, pp. 11–18, 1899.
[52] England, P.C., Molnar, P., and Richter, R.F.M., Kelvin, Perry and the age of the Earth. *American scientist*, **95**, pp. 342–349, July-August 2007.
[53] Holmes, A., *The Age of the Earth*, Nelson: London, 1937.
[54] Thomson, W. and Tait, P.G., *Elements of Natural Philosophy*, 2nd edn, Oxford: Cambridge 1879. x