John Joly (1857–1933) and his determinations of the age of the Earth

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Abstract: John Joly (1857–1933) was one of Ireland's most eminent scientists of the late nineteenth and early twentieth centuries who made important discoveries in physics, geology and photography. He was also a respected and influential diplomat for Trinity College, Dublin, and various Irish organizations, including the Royal Dublin Society. Measuring the age of the Earth occupied his mind for some considerable time – a problem he was to address using a diverse range of methods. His sodium method of 1899, for which he is best known, was hailed by many as revolutionary, but it was later superseded by other techniques, including the utilization of radiometric dating methodologies. Although Joly himself carried out much research in this area, he never fully accepted the large age estimates that radioactivity yielded. Nevertheless, Joly's work in geochronology was innovative and important, for it challenged earlier methods of arriving at the Earth's age, particularly those of Lord Kelvin. Although his findings and conclusions were later discredited, he should be remembered for his valuable contribution to this important and fundamental debate in the geological sciences.

John Joly was born on 1 November 1857 in Hollywood House (the Rectory), Bracknagh, County Offaly, the third and youngest son of the Reverend John Plunket Joly (1826–1858) and Julia Anna Maria Georgina *née* Comtesse de Lusi. The Joly family originated from France, but came to Ireland from Belgium in the 1760s. Joly's great-grandfather served as butler to the Duke of Leinster who gave the living of Clonsast parish to the family in the early 1800s (Dixon 1934; Nudds 1986).

After his father's sudden death at a young age, the Joly family moved to Dublin where John Joly received his secondary education at the celebrated Rathmines School in which he was enrolled from 1872 to 1875. Although he did not excel in the classroom, he was popular, nevertheless, and became known as 'The Professor' on account of his tinkering with chemical apparatus and other gadgets. In 1875 after a bout of poor health Joly spent some time in the south of France, before returning to Dublin in 1876. He then entered Trinity College, Dublin, where he remained for the rest of his life. He followed courses in classics and modern literature, but later concentrated on engineering. In 1882 he sat for the degree of Bachelor of Engineering and gained first place and certificates in several subjects including engineering, experimental physics, mineralogy, geology and chemistry.

In adulthood Joly was a distinctive and unforgettable man. Tall, with hair swept off his forehead, a bushy moustache, and pince-nez perched on his nose (Fig. 1), he spoke with what was considered to be a foreign accent, but in reality the rolled r's were simply used to conceal a slight lisp (Dixon 1941). He was a keen traveller and made many trips, especially to continental Europe and the Alps, with his lifelong friend Henry Horatio Dixon (1869–1953), one-time professor of botany at Trinity College, Dublin. Joly loved the sea and was a notable yachtsman who made frequent voyages along the western seaboard of the British Isles. He also served as a Commissioner of Irish Lights and carried out some work for the Admiralty on signalling and safety at sea (Nudds 1986, 1988).

Academic career

Although Joly considered a career abroad, he acceded to his widowed mother's wishes and remained in Ireland, at Trinity College, Dublin. There he was employed to carry out some teaching and to assist in the research of the professor of civil engineering. During this time (1882–1891) he was able to engage in a great deal of research, although this was largely in aspects of physics and mineralogy, rather than engineering. As with most experimental research of this period, apparatus did not exist, or was not available, and so had to be invented and built by the researcher himself. Among the first pieces invented by Joly were a new photometer and a hydrostatic balance.

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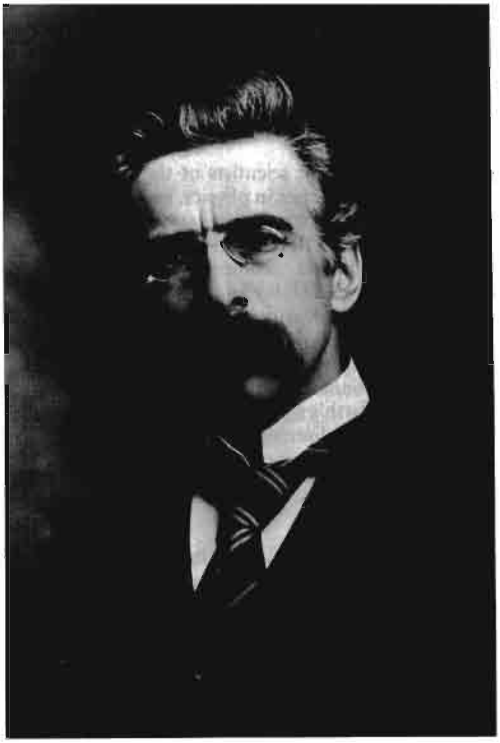

Fig. 1. John Joly (1857–1933), professor of geology and mineralogy, Trinity College, Dublin. Photograph taken May 1901 (courtesy of the Department of Geology, Trinity College, Dublin).

It was during this time that he developed an interest in mineralogy and began to accumulate a large collection of very fine Irish, continental and American mineral specimens (Wyse Jackson 1992).[1] He invented the steam calorimeter for measuring the specific heat of minerals. At the same time he worked on the density of gases and the detection of small pressures, and the steam calorimeter later played an important role in the kinetic theory of gases (Somerfield 1985).

In 1891 Joly was appointed assistant to George Francis Fitzgerald, professor of natural and experimental philosophy, and the following year he was elected a Fellow of the Royal Society (of London), an indication of how important his contemporaries considered his work to be. Surprisingly, he was not admitted as a member of the Royal Irish Academy for another five years. Over the ensuing years he addressed a tremendous range of scientific subjects. In 1894, together with Dixon, he published an important paper that explained for the first time the mechanism of the ascent of sap in trees and plants, and in 1895 Joly exhibited colour slides to the Royal Society. His method, the 'Joly process of colour photography', was the first successful process of producing colour photographic images from a single plate. However, his assertion that he had invented the technique was challenged by an American. Legal battles ensued but although Joly's priority was finally established, the process was soon superseded by other methods. Nevertheless, the 'Joly process' is important as it is essentially the method used in colour photography today.

In 1897 Joly succeeded William Sollas in the chair of geology and mineralogy at Trinity College, a position he retained until his death in 1933. Unlike his predecessors Joly was essentially a physicist, not a geologist, and consequently he published little on the geology of Ireland. He carried out much research on minerals, but it was his work on radioactivity and radium that was his most important. This led to the establishment of the Irish Radium Institute in 1914, which exploited the medical advantages of the radioactive element.[2] But Joly also worked on determining the age of the Earth, and it is for his contributions to this debate that he is now best remembered.

Joly's sodium method

Joly's contribution to the question of the age of the Earth was one of a number made by Irish-born or Irish-based academics (O'Donnell 1984; Wyse Jackson 1992) (Table 1). The first was that of Archbishop James Ussher, who in the seventeenth century arrived at a date of 4004 BC from a reading of biblical events (Reese *et al.* 1981; Brice 1982; Fuller 2001). Others included Belfast-born William Thomson (later Lord Kelvin) who argued, based on the cooling rate of an initially molten planet, that the Earth was between 20 and 400 million years old (Thomson 1864). However, his last paper on the subject, published in 1899, firmly placed the limits between 20 and 40 million

[1] The collection is still on display in the Geological Museum, Trinity College, Dublin.

[2] In Ireland Joly pioneered the medical benefits of radioactivity. With a Dublin doctor, Water Clegg Stevenson (1876–1931), Joly established the Radium Institute at the Royal Dublin Society in 1914 whose work was in treating cancer patients (Joly 1931). Their 'Dublin method' was the first to utilize radium emanation (radon) enclosed in hollow needles in the treatment of tumours (Murnaghan 1985). Joly was very proud of this work.

Table 1. *Estimates of the age of the Earth made by various Irish-born or Irish-based* scientists*

Author	Age determination	Date	Method
James Ussher	4004 BC	1650	Biblical chronology
William Thomson (Lord Kelvin)	20–400 Ma	1864	Cooling Earth
Samuel Haughton	2298 Ma	1865	Cooling Earth
Samuel Haughton	1526 Ma	1871	Sediment accumulation
Samuel Haughton	200 Ma	1878	Sediment accumulation
William Sollas*	17 Ma	1895	Sediment accumulation
William Thomson (Lord Kelvin)	20–40 Ma	1899	Cooling Earth
John Joly	90–100 Ma	1899	Sodium accumulation
John Joly and Ernest Rutherford	20–470 Ma (Devonian)	1913	Pleochroic halos
John Joly	47–188 Ma	1915	Sediment mass
John Joly	300 Ma	1923	Thermal cycles
John Joly	300 Ma	1930	Sodium accumulation
Edward J. Conway	700–2350 Ma	1943	Ocean chemistry

years (Thomson 1899), a value that antagonized many geologists (Dalrymple 2001; Shipley 2001). Samuel Haughton and William Sollas, Joly's predecessors at Trinity College, Dublin, also entered the geochronological debate, and their contributions are discussed below.

Joly's first documented thoughts on the antiquity of the Earth were in written verses penned on 28 August 1886 in the Wicklow Mountains south of Dublin (Nudds 1983). One sonnet considered the age of the enigmatic trace fossil *Oldhamia antiqua* Forbes from the Cambrian slates of Bray Head, which Joly suggested was a witness to the long, slow changes that had affected the Earth:

Is nothing left? Have all things passed thee by?
 The stars are not thy stars! The aged hills
 Are changed and bowed beneath repeated ills
Of ice and snow, of river and of sky.
The sea that raiseth now in agony
 Is not thy sea. The stormy voice that fills
 This gloom with man's remotest sorrow shrills
The memory of the futurity!
 We – promise of the ages! – Lift thine eyes,
 And gazing on these tendrils intertwined
 For Aeons in the shadows, recognize
 In Hope and Joy, in heaven-seeking Mind,
 In Faith, in Love, in Reason's potent spell
 The visitants that bid a world farewell!

Joly's first scientific foray into the matter of geochronology came thirteen years later with the publication of his first and probably most celebrated, if somewhat controversial, paper on the subject (Joly 1899). Simply put, Joly examined the rate of sodium input into the oceans and by simple mathematics arrived at an estimate for the age of the Earth. The idea came to him whilst sailing off the east coast of Ireland with Henry Dixon in 1897, collecting coccoliths and plankton from the Irish Sea (Dixon & Joly 1897, 1898) and observing the feeding behaviour of seabirds (Joly 1898).[3]

At that time Joly was unaware, as were his contemporaries, of the pioneering work of the English astronomer Edmond Halley (Cook 1998). In 1715 Halley had proposed to the Royal Society that salt concentrations in lakes that had no discharge rivers, should be measured every 100 years, as he considered that from the incremental increase of the salt, the age of the lake could eventually be deduced. Once enough data had been collected over time, inferences about the age of the ocean, and therefore of the Earth, could be drawn from the results. While Halley accepted that mankind had dwelt upon the Earth for about 6000 years, as stated in the Scriptures, he also considered that it was 'no where revealed in Scripture how long the Earth had existed before this last Creation' (Halley 1715, p. 296). He thus regretted that the ancient Greek and Latin authors had not recorded the saltiness of the sea 2000 years ago, since 'the World may be found much older than many have hitherto imagined' (Halley 1715, p. 299). He therefore recommended to the Society that experiments be started 'for the benefit of future Ages'. But the Society does not seem to have heeded his advice and Halley's idea was only rediscovered in 1910 (Becker, 1910*a*).

Although aware of Mellard Reade's important book of 1879, Joly was unaware of his valuable paper published in the *Proceedings of the Liverpool Geological Society* in 1877, which examined the volume of sulphates, carbonates and chlorides in the oceans, and their rate of

[3]Joly had bought a yacht, *Gweneth*, soon after his appointment to the chair of geology and mineralogy, which carried a salary of £500 per annum.

accumulation. Using this information Reade calculated the time taken for the oceans to reach their present concentration of these substances: 25 million years, nearly half a million years, and 200 million years respectively for sulphates, carbonates and chlorides. These figures gave an estimate of the minimum age of the Earth (Mellard Reade 1877, p. 229). Although Joly later acknowledged these pioneering publications of Halley and Mellard Reade he noted, without explanation, that their schemes, unlike his, would not have produced reliable results (Joly 1915).

Brilliant in its simplicity, Joly's paper of 1899 fired the imagination of both scientific and general audiences, and for perhaps a decade his 'sodium method' held sway amongst geochronologists. It relied upon a number of assumptions, and on data regarding ocean and river characteristics published by John Murray in the 1880s. The fundamental tenet was the uniformitarian stance that the rates of denudation of sodium-bearing rocks, and the discharge of the rivers into the oceans, had remained uniformly constant over geological time. The age of the Earth was thus derived by the simple formula:

$$\text{Earth's age} = \frac{\text{Volume of sodium in the ocean}}{\text{Rate of annual sodium input}}$$

which yielded an age of 90–100 million years.

Joly read his paper to the Royal Dublin Society at a meeting in Leinster House on 17 May 1899, and it was published several months later in September in the *Scientific Transactions*, the premier journal of the Society. Reactions to his ideas began to appear in the scientific press within six months. Review articles were published in several journals, including the *American Journal of Science* (Anon. 1899) and *Geological Magazine* (Fisher 1900), but the Reverend Osmund Fisher's review was by far the most testing, because, he argued, the processes invoked by Joly were *not* uniform throughout geological time. Additionally, Fisher suggested that Joly's figures for the volume of sodium delivered into the oceans by rivers might be at fault, and that Joly did not take into account the effect of 'fossil sea water' which, Fisher noted, was trapped in sediments and elsewhere. Fisher also suggested that Joly's estimate, that 10% of the sodium chloride came from rainwater, was too high. Finally he made a little swipe at Joly's written style which he contended was rather convoluted and not very clear. He has a point. These minor criticisms aside, Fisher recognized that Joly's essay had 'opened up an entirely new line for the investigation of geological time' (Fisher 1900, p. 132).

William Ackroyd, Public Analyst for Halifax, was of the opinion that a great deal of the oceanic salt was transported back onto land; he put this figure at 99%, and on the basis of this recalculated the age of the Earth and derived an age of 8000 million years (Ackroyd 1901*a*). This was the first offering in a public debate on Joly's theory played out in the pages of *Chemical News* and *Geological Magazine* (Ackroyd 1901*a, b, c, d*; Joly 1901*b, c*). Ackroyd argued that it was important to know the ratio in river water of transported (or recycled) sea salt and that derived from rocks through solvent denudation. He included data that demonstrated that only 0.02% of the chlorides in the water of Malham Tarn near Craven were derived from the surrounding limestones. From this one must assume he considered that most were derived from atmospheric water. In his papers in *Geological Magazine* (Ackroyd 1901*c, d*) he criticized Joly for not appreciating the significance of this work or for ignoring it altogether.

At the British Association for the Advancement of Science meeting held in 1900 at Bradford, Joly's findings must have created quite a stir as his report was ordered by the general committee to be published *in extenso* (Joly 1900*c*). William Sollas, in his presidential address to Section C – Geology, sided with Joly's finding, stating that 'there is no serious flaw in the method, and Professor Joly's treatment of the subject is admirable in every way' (Sollas 1900). Sollas, however, did question the reliability of the data concerning the river discharge of sodium (Sollas 1900). Later papers by Sollas (1909), Becker (1910*b*) and Clarke (1910) laid minor criticisms at Joly's door. Sollas suggested that some modification could be made for the fact that volcanic activity was at certain times in the past more pronounced that at present times, and that this would have had some effect on the supply of sodium to the oceans. In addition he argued that modern ocean water, at normal temperature, had only a slight corrosive effect on salt contained in rocks. At higher temperatures of between 180°C and 370°C far higher volumes of sodium would have been dissolved. From this we surmise that Sollas believed that the early oceans were considerably hotter than those of today. Sollas recalculated the annual discharge of the rivers from which he derived a date of 78 million years for the age of Earth, but suggested that it lay within the range 80–150 million years. Clarke (1910) examined the rate of removal of sodium from the landmass and arrived at a figure of 80 million years, while Becker (1910*c*) suggested that Joly's figure of 10% for the contribution of sodium recycled from the atmosphere was closer to 6%. Subsequently, a considerable number of papers also discussed Joly's sodium method (for example, Rudzki 1901) which were either in broad agreement with his ideas (e.g. McNairn 1919) or raised a number of objections (see for example Shelton 1910, 1911; Holmes 1913). Shelton said that while Joly's scheme was instructive, some of the underlying foundations on which it was based needed careful consideration. Joly, Shelton argued, did not make adequate allowance for salt recycled via the atmosphere, nor for fossil salt contained in sedimentary rocks. Shelton also noted that Joly's age determination was based on analyses of sodium content, which given the accuracy of instrumentation available could not be done with any great accuracy. In particular, Arthur Holmes reasoned that the rocks would have had to lose more sodium into the oceans than they had ever contained, for Joly's figures to add up.

Joly's responses to these criticisms (Joly 1900*b*, 1901*b*, *c*) strongly reinforced his uniformitarian principle; however, he did accept that his estimate of the role of rainwater in providing sodium chloride might have been underestimated and required further experimental work. With respect to fossil seawater Joly stated that it could only have contributed 0.9% of oceanic sodium chloride and, as such, was negligible. His response to Sollas was that 'there is much reason to believe that the nineteen rivers ... afford an approximation as to what the world's rivers yield' (Joly 1900*c*). Indeed, he stated in 1911 that the findings of Sollas, Becker and Clarke, together with his own, gave concurrent results of circa 100 million years, and proudly anticipated that this determination would not be 'seriously challenged in the future' (Joly 1911*a*).

Joly went further in defence of his ideas, in that he devised various experiments which he hoped would generate acceptance of some of his theoretical assumptions made in 1899. One of these was to invent a fractionating rain-gauge (Joly 1900*a*), which he hoped would allow him to collect rainwater over incremental time periods. Subsequent analysis of the amount of dissolved sodium chloride in this rainwater would enable him to quantify the volume of sodium in the oceans from this pluvial source. While demonstrating how his rain-gauge would operate, Joly fails to record whether it was ever put to use or was effective!

Joly also examined the rate of solution of various igneous materials in fresh and salt water (Joly 1900*d*) which showed that of the four tested (basalt, orthoclase, obsidian and hornblende) the basalt from the Giant's Causeway in County Antrim dissolved more readily than the others, and that salt water was a more effective solvent than fresh water. Not surprisingly, the obsidian proved the most resistant to solution. Joly noted that his results for the rates of denudation were far lower than those demonstrated by field study and he argued that additional factors such as organic acids, wetting and drying, and other erosive processes were more important than solution of rocks by water. Nevertheless, he made an allowance for the solvent action of the ocean, by reducing his age estimate by a few million years to 96 million (Joly 1911*a*).

After the initial peak of interest that closely followed on from his 1899 paper, many of Joly's subsequent papers on the subject were simply reports of lectures, or reiterations of the original theory. In 1915 with the publication of *Birth-time of the World* (Joly 1915) there followed renewed interest in the sodium method – but it did not last. The theory was finally consigned to the scientific scrap-heap by several geologists (Harker 1914; Barrell 1917; Gregory 1921; Chamberlin 1922) who, in the damning words of Arthur Holmes, 'rejected it as worthless' (Holmes 1926, p. 1056). By the mid-1920s the scientific community was focused on the new theories based around radioactivity (Lewis 2001). Paradoxically Joly also carried out much useful research in this developing area, but he himself could never consign his sodium method to the waste basket, although by 1930 he had accepted some major modifications suggested by A. C. Lane in 1929, which pointed at a figure of 300 million years for the method (Joly 1930).

Unusually, and perhaps uniquely for publications of the Royal Dublin Society, a second impression of the original paper had to be produced in November 1899 as all the stocks had been distributed and demand continued. This allowed Joly to rectify a number of small errors that had appeared in the appendix of the first impression. The paper was also printed in North America in its entirety in the *Annual Report of the Smithsonian Institution* for 1899, and so Joly's ideas and methodologies were rapidly transmitted throughout the scientific community on either side of the Atlantic (Joly 1901*a*). It was an important contribution to the growing body of scientific opinion that refuted the low estimate of the age of the Earth of 20–40 million years propounded by Kelvin (see, for example, Shipley 2001), which was eventually dispelled with the advent of radioactive dating methods.

It is interesting to note that it is now thought that on the basis of the volume of chloride contained in brines found in deep-seated groundwater, the salinity of the earliest oceans is considered to be 1.5 to 2 times saltier than that of today (Knauth 1998*a*, *b*). Thus the oceans are not becoming progressively saltier through the release of sodium and chloride during denudation, as was Joly's contention. Quite the contrary, Knauth (1998*a*) argued that if all the present deposits of subsurface salt were returned to the oceans, they would be 30% saltier than at present.

Sediment accumulation

At the same time as the 'sodium method' was gaining acceptance, others continued to estimate the age of the Earth using sediment accumulation as their gauge. This method owed its origins to the work of John Phillips in 1860 (Phillips 1860; Morrell 2001) who determined the thickness of the global sedimentary pile and, using a figure for the rate of sedimentation, arrived at 96 million years for the age of the Earth. Many other calculations using this method followed (see Lewis 2001), perhaps the most celebrated of which were those of the Reverend Samuel Haughton, third professor of geology at Trinity College, Dublin. Haughton, who was a supporter of Kelvin's methods for estimating the age of the Earth and an opponent of Charles Darwin's theory of evolution, initially achieved an astonishing estimate of 2298 million years, based on the same principles as those used by Kelvin (Haughton 1865). In the context of sediment accumulation, however, Haughton is remembered for his principle that 'the proper relative measure of geological periods is the maximum thickness of the strata formed during these periods' (Haughton 1878), which of course necessitated a global estimate of the maximum thickness of each sedimentary sequence, and the determination of the rate at which those sediments accumulated. Using this principle he first published an age for the Earth of 1526 million years (Haughton 1871), but uncomfortable with the vast timescales he was deriving, which were in stark contrast to those deduced by Kelvin, seven years later he attempted the calculation again – and arrived at much the same answer. This time, however, he conceded: 'If we admit (which I am by no means willing to do) that the manufacture of strata in geological times proceeded at *ten times* this rate, or at the rate of one foot for every 861.6 years ... This gives for the whole duration of geological time a *minimum of two hundred million years*' (Haughton 1878, p. 268), a value much more acceptable to the wider geological community. Much later Arthur Holmes argued that the uniformity of sedimentation rates assumed by Haughton was incorrect and that his principle would be better stated as 'the time elapsed since the end of any geological period is a function of the sum of the maximum thicknesses accumulated during all the subsequent periods.' (Holmes 1947, p. 119).

By the 1890s the methodology had become the standard means of measuring the age of the Earth and a great many authors attempted it, including Charles Doolittle Walcott in the United States who derived a date of 35–80 million years based on measured sections in North American sedimentary basins (Walcott 1893), and Mellard Reade in England who estimated that 'The time that has elapsed since the commencement of the Cambrian is therefore in round figures 95 millions of years' (Mellard Reade 1893, p. 100). In 1895 William Johnston Sollas, fifth professor of geology at Trinity College, following Haughton's principle, calculated the Earth's age to be 17 million years (Sollas 1895), one of the lowest figures ever established. However, a later calculation, based on a total sediment thickness of 335 000 feet or 63 miles, and sedimentation rates of 3 and 4 inches per century resulted, respectively, in ages of 148 and 103 million years (Sollas 1909). Sollas noted though, that it was difficult to determine accurately the rate of sediment accumulation, which he acknowledged could be anything between 2 and 12 inches per century.

Joly was delighted since these dates largely concurred with his and thus confirmed the strength of his sodium method determination. In 1909 he examined Sollas' figures for himself and agreed with his results (Joly 1911*a*). However, in 1914, in a lecture to the Royal Dublin Society, he argued that sediment mass, not thickness, was a more accurate measure, which widened Sollas' results to a minimum of 47 million years and a maximum of 188 million years. Then, on the basis that he believed sedimentation rates were not uniform through geological time (Joly 1915), he reduced the mean of these limits, 117 million years, to a figure of 87 million years which concurred well with his sodium method results. This marked a change in the uniformitarian stance that he had adopted in 1899 for the rate of sodium accumulation in the oceans.

By 1910 these methods were being supplanted by the age determinations generated by radioactive decay methods. Although in its infancy, the study of radioactivity was beginning to yield ages for the Earth that were considerably older than 100 million years.

Radioactivity and pleochroic halos

Joly was just one of many scientists drawn into the field of radioactivity following its discovery by Henri Becquerel in 1896 and the subsequent discovery of radium by Marie and Pierre Curie in 1898. By 1904 Ernest Rutherford had already suggested that the presence of radioactive minerals might provide a measure of the age of those minerals (Rutherford 1905), and by 1905 Robert Strutt (later Lord Rayleigh) reported widespread presence of radioactive elements in rocks. Over the next five years he went on to examine helium as a means of determining ages. In the United States in 1907 Bertram Boltwood was the first researcher to examine the uranium–lead series (Badash 1968; Dalrymple 2001) and, using this method, in 1911 Arthur Holmes published a date of 1640 million years for the Archaean of Ceylon (Holmes 1911; Lewis 2001). Immediately Joly was on the back-foot defending his geochronology from these new data. In his book *Radioactivity and Geology* (Joly 1909*c*) and in an important paper entitled 'The Age of Earth' Joly (1911*a*) questioned whether the decay rate of uranium had been constant throughout geological history, as suggested by others. He said that this assumption was without strong basis and that the calculations of age limits were based on derived radioactive products, rather than radioactive parent elements. Turning to his own previous methods for support of his unease, Joly noted that the extremely slow rates of sediment accumulation implied by these vast ages were difficult to credit:

> If the recorded depths of sediments have taken 1400 million years to collect, the average rate has been no more than one foot in 4000 years! This seems incredible: and if we double the depth of maximum sedimentation it still remains incredible. But, if possible, still more incredible is the conclusion respecting solvent denudation to which radioactivity drives us. If the sodium in the ocean has taken 1400 million years to accumulate, the rivers are now bearing to the sea about 14 times the average percentage of the past ... It seems quite impossible to find any explanation of such an increase (Joly 1911*a*, p. 379).

Joly was not alone in his concerns – the American geochronologist George Becker also voiced unease with radiometric dates, as did the American Committee on the Measurement of Geological Time by Atomic Disintegration, which reported that uranium as a whole decayed more rapidly in the past, and therefore the dates derived from it could be overestimated by 25% (Lane 1925). Lane was in fact ahead of his time in recognizing that uranium might have several isotopes (not confirmed for another four years, and U^{235} was not discovered until 1936) and thus 'as a whole' (averaging all isotopes) uranium appeared to have decayed more rapidly in the past. U^{235} decays six times as fast as U^{238}. Holmes (1913), though, considered it highly unlikely that radioactive decay rates had varied through geological time: as unlikely as finding that the laws of physics and chemistry had changed over time!

Joly's first paper on radioactivity and geology was published in *Nature* in 1903 where he discussed the potential of using radium to date the age of the Earth (Joly 1903). In a number of later papers published in 1908 and 1909 he calculated the volume of radioactive elements, including radium and thorium, in terrestrial and oceanic rocks of various ages (Joly 1908*b*, 1909*a*),[4] and from seawater (Joly 1908*a*, 1909*b*). Much of this work received widespread release in his book *Radioactivity and Geology* (Joly 1909*c*), and the outcome of this study was formulation of his ideas pertaining to internal heat sources in the Earth, which had implications for a later geochronological method.

In 1907 Joly realized that small dark rings, or pleochroic halos as they came to be known, which he had observed in biotite in some granites, were the products of radioactive decay in zircons enclosed within the biotite crystals (Joly 1907*a*) (Fig. 2). Previously it had been suggested that these were due to the presence of organic pigments in the minerals, but Strutt had earlier demonstrated the radioactive properties of zircon, to which Joly attributed the halos. The size of the halo was related to the type of radioactive decay product and the range of the rays produced (Joly 1911*b*), while the intensity, he argued, was due to the duration of radioactive decay. He observed complex halos with distinctive inner and outer rings, or corona, in a greisen from Saxony in Germany (Joly 1910), and soon afterwards he and his research assistant, Arnold

[4] It would be interesting to re-examine Joly's rocks from the Simplon and St Gothard tunnels through the Alps (Joly 1907*b*, 1912), now housed in the Geological Museum in Trinity College, Dublin, to determine how accurate his results were. Do they match with modern calculations of the radioactive elements contained in these rocks? If not, what does this say about Joly's methodologies or the reliability of his equipment? Perhaps, as Léo Laporte has pointed out, any differences may result from the different half-lives then in use.

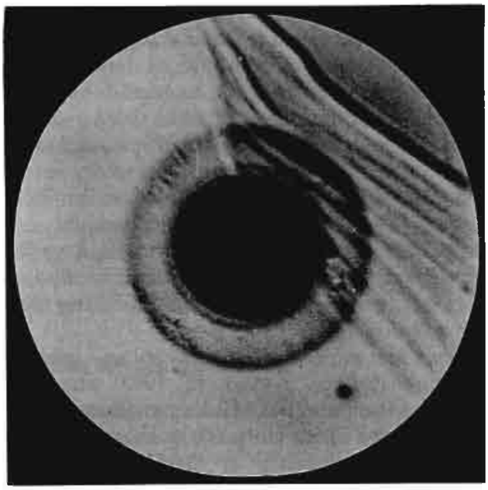

Fig. 2. A single pleochroic halo developed in biotite in the Leinster granite from Garryellen, County Carlow, Ireland. The inner dark disc is due to radon (a gas derivative of radium); the succeeding inner ring is due to radium A alpha decay while the outer darker ring was produced by radium C alpha decay (from Joly 1911*b*, plate III, fig. 4).

Lockhart Fletcher, attributed the development of the outer rings to the alpha decay of radium C (now known as the isotope bismuth^{214}) while the inner rings were produced by radium A (now known as the isotope polonium^{218}) (Joly & Fletcher 1910). Joly was also able to distinguish halos produced by other radioactive sources including thorium and uranium, and the radii of the halos produced by the thorium and uranium decay series were given in the Huxley Lecture that Joly delivered in Birmingham in October 1912 (Joly 1913).

In 1913 Joly and Ernest Rutherford developed a unique methodology to date a rock based on its pleochroic halos, which required knowledge of the mass of the nucleus of the halo and the number of alpha rays required to produce a certain intensity of halo. Using specimens from the Leinster Granite,[5] Rutherford, working in Manchester, produced artificial halos in mica and measured the number of alpha rays required to produce them. Meanwhile, in Dublin, Joly measured the mass of the nuclei. Between them they tabulated the ages of 30 halos which ranged from 20 to 470 million years. They concluded that the age of the Devonian was not less than 400 million years, which concurred with results found by Holmes two years earlier; however, a proviso read: 'that if the higher values of geological time are so found to be reliable, the discrepancy with estimates of the age of the ocean, based on the now well-ascertained facts of solvent denudation, raises difficulties which at present seem inexplicable' (Joly & Rutherford, 1913, p. 657).

Three years later Joly measured halos in younger rocks from the Vosges (Joly 1917), and later still he measured the radii of rare halos in the Tertiary granites from the Mourne Mountains. The radii of the latter were 7% smaller than those of the Leinster Granite, which themselves were 10% smaller than those he had recognized in Archaean rocks (Joly 1923*b*). Joly concluded in triumph: 'It would seem as if we might determine a geological chronology on the dimensions of these halo-rings!' (Joly 1922*a*).

No sooner had he come to this exciting conclusion than he discovered small halos in Archaean rocks from Norway. His first specimens of this material had been lost when his laboratory at Trinity College was occupied by troops during the Easter Rebellion in 1916 (Joly 1920). Six years later he received fresh material and discovered the small halos which he concluded represented full decay of a radioactive element that was no longer present in the Earth's crust. He called this new radioactive element 'hibernium' after his homeland (Joly 1922*b*) it was later found to be samarium.

In 1922, Joly reiterated his contention that radioactive decay rates were not constant throughout geological history. This was partially based on his observations of halos whose characteristics were not consistent. In particular, the innermost rings produced by uranium in some halos were not consistent with the known ionization curves of uranium alpha particles. He suggested that these rings were caused by the faster decay of uranium in the past, or by the decay of a uranium isotope that was no longer present. The fact that thorium halos of all ages were constant in size was also difficult to explain (Joly 1922*a*). Holmes (1926) argued that the inconsistencies of the uranium halos were due not to time but to other factors, including the presence of the recently discovered rare isotope, actinium. Nevertheless, he accepted that Joly's scheme of correlating halo radii with time would eventually give a scale against which the ages of other halos could be determined.

Subsequently, however, Joly's halo data were examined, and the accuracy of his measurements was questioned by Kerr-Lawson (1927) who was unable to detect the differences in radii that Joly had claimed. Nevertheless, his imaginative attempt to employ pleochroic halos as a measure for geological time was noteworthy.

[5] County Carlow in Ireland.

Joly's objections to dates derived by radiometric methods were also rejected by the late 1920s when further information about isotopes, atomic weights and other radioactive elements became available (e.g. Holmes & Lawson 1927). Holmes, who was at the forefront of radiometric research (Lewis 2001), argued that, at worst, errors of a few percent might be attributed to the unranium–lead methodology (Holmes 1926).

Earth's surface history and thermal cycles

Joly's final contribution to the geochronological debate came about from his interest in isostasy, the internal heat of the Earth, and its signature on the surface of the Earth. Kelvin's ideas on a cooling Earth were long dismissed, and it had been recognized by Strutt and Joly that the Earth had an internal heat source, resulting from decay of the radioactive elements it contained. Joly's pioneering suggestion was that the internal heat of the Earth built up over a period of time (Joly 1909*c*).

By 1923 Joly had developed a theory in which he explained that the surface features seen on the Earth were formed as a direct result of its own internal heat source. This theory subsequently became known as the theory of 'thermal cycles' (Joly 1928). The heat source was responsible for the melting of the basaltic crustal horizons (termed the basaltic magmatic layer by Joly) that lay beneath the continental crust. The continents, which he described as 'granitic scum' (Joly 1925, p. 176), rested directly in isostatic balance on a basaltic magmatic layer that was up to 70 miles in thickness, and which enclosed the whole globe. The water that made up the oceans simply filled the voids between the continents. In a thermal cycle, he explained, this basaltic magmatic layer melted periodically due to the build-up of heat generated by radioactive decay. Melting led to changes in the volume of this horizon beneath the continents, which in turn generated tidal currents in the basaltic magma. Joly argued that such a change in volume could have resulted in an increase in the diameter of the Earth, and that the continents would have been isostatically buoyed up. This effect would have been negated by the resultant sinking of the continental masses due to the decreased density of the molten layers, and consequently there would have been widespread transgressive events.

What is interesting is what Joly speculated happened on cooling of the molten basaltic magmatic layer. Heat was lost as it migrated from beneath the continental areas to oceanic regions, from where it was largely lost into the oceans (Joly 1923*a*). Joly argued that the cooling of the melted level caused it to recrystallize and shrink, and that continents would return through a series of vertical movements to their former isostatic levels. He pointed out, quite correctly, that vertical movements were often associated with lateral or horizontal Earth movements. Both, he argued, were generated by the same thermal processes outlined above. But how did he explain the orogenesis that was also a feature of these complex processes? He postulated that the most lateral movement occurred when the basaltic level beneath the continents was in a molten state, at which time it would have had a similar density to the granitic continental masses above. Beneath the oceans thermal currents significantly reduced the thickness of the basaltic magmatic layer, which he deduced would have cracked, and which would have seen the injection of new basalt. The area of the ocean floor thus increased significantly, and this increase in area resulted in the generation of compressive forces which forced the oceanic floor to press against the margins of the continental crust. This initiated orogenesis or mountain building. Joly estimated that these orogenic events or 'revolutions', as they were called, took place once every 50 million years or so. He tabulated five or six revolutions of different ages which he correlated with various mountain orogenic belts. These included the Caledonian, Appalachian and the Alpine 'revolutions'. From the evidence of global tectonics, Joly considered that the Earth was 300 million years old.

Many of his ideas on global tectonics were articulated in his book *The Surface History of the Earth* (Joly 1925, 1930) and in his papers on thermal cycles (Joly 1928) and the Earth's surface structure (Joly & Poole 1927). Naturally he entered the debate on continental drift and argued that there was evidence that the continents drifted westwards. This delighted some Irish wags, who highlighted in the popular press this scientific proof that Ireland was moving further away from England.

Joly's ideas on global tectonics were typically complex and imaginative, and certainly deserve fuller examination and assessment – this is beyond the scope of this present paper. Greene (1982) has discussed the evolution of tectonic theory at length, from forerunners such as Elie de Beaumont and Eduard Suess, to those later geologists that included Joly, who worked on what Greene termed 'the fourth global tectonics'. Oreskes (1999) also analyses in depth Joly's contribution to the theory of continental drift.

Conclusion

As early as 1922 Joly noted that the expression the 'age of the Earth' was ambiguous (Joly 1922*a*), and it can now be seen that Joly's own position on this matter was also ambiguous. In 1930, in the second edition of his *Surface History of the Earth*, published three years before his death, he wrote: 'the age of the Earth is not the same as geological time' (Joly 1930). It is my contention that Joly understood 'age of the Earth' to mean the time since the onset of denudation and biological processes, while 'geological time' included older Archaean times. In essence, Joly was taking a philosophical stance which allowed his low age estimates to stand as correct estimates for the age of the Earth, yet at the same time he did not reject out of hand the accepted estimates of Holmes and others, derived by radiometric means, which gave a longer measure of geological time. Nevertheless, he remained sceptical of dates determined by radiometric methods.

In the light of his work on radioactivity it is somewhat surprising that Joly did not accept that his sodium method yielded erroneously low age estimates, or acknowledge that what it measured was not the age of the Earth, but an estimate of the age of the oceans. Although it is clear today that the oceans are older than Joly's method might suggest, his sodium method actually gives a good measure of the residence time of sodium in the oceans, which is approximately 260 million years (Mittlefehldt 1999). Up until his death Joly continued to hold the view that 300 million years was a good estimate of the age of the Earth.

Joly's age methodologies and breadth of research in geochemistry, mineralogy and radioactivity made a major contribution to the debate on the age of the Earth played out at the end of the nineteenth and beginning of the twentieth centuries. His sodium method held centre-stage among geologists and geochemists for some years, and stimulated much debate on the subject of the age of the Earth. Additionally, Joly's unique attempts to employ pleochroic halo radii as measures for geological time were extremely valuable and, in the light of the exciting avenues opening up in the field of radioactive research in the first decades of the 1900s, may well have appeared to have the distinct potential to estimate the actual age of the Earth. Even though it was subsequently demonstrated that the ratio between original radioactive elements and their decay derivatives yielded better estimates of the age of the Earth, Joly's many faceted investigations on the subject helped to stimulate research that ultimately led others to the geochronological methodologies in vogue today.

Joly spent all of his professional life working in Trinity College, Dublin, during which time he wrote 269 scientific papers and several books, including an autobiography. He was the recipient of many awards and had a high international reputation. He was a Fellow of the Royal Society which awarded him the Royal Medal in 1910, and he received the Boyle Medal of the Royal Dublin Society in 1911 and the Murchison Medal (of the Geological Society of London) in 1923. He became a Fellow of Trinity College in 1919 (the first person in 250 years who did not have to pass a rigorous examination) and was president of the Royal Dublin Society (1929–1932). He was conferred with the honorary degrees of Doctorate of Literature from the University of Michigan, and Doctorate of Science from the University of Cambridge and the National University of Ireland. Forty years after his death he was honoured by having a crater on Mars named after him (Batson & Russell 1995), which is appropriate given Joly's work on the nature and origin of Martian 'canals' (Joly 1897).

He was by all accounts a very popular man, loved and respected by many. On his death many friends contributed to a memorial fund that is still used to promote an annual lecture on a geological theme, which is usually given by a leading foreign authority. In addition his name and memory are perpetuated by the Joly Geological Society, the student geological association of Trinity College, Dublin, founded in 1960.

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