Classic Paper in the History of Geology

John Joly's paper: "Uranium and Geology" (1908)

In 1908 the British Association for the Advancement of Science met in Dublin, and the Irish geologist and physicist John Joly (1857—1933) served as President of Section C: Geology. For his address he took the theme of "Uranium and Geology" — and in this summation of his work on radioactive materials in rocks, published the following year, he discussed their role in the generation of the Earth's internal heat.

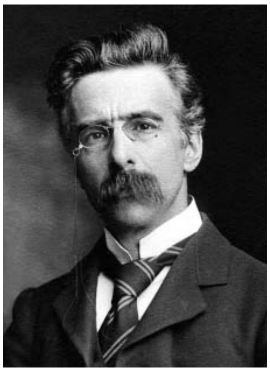

Figure 1 John Joly in 1901. Photograph by A.G. Werner and Son, 39 Grafton Street, Dublin. [Geological Museum, Trinity College, Dublin collection].

John Joly (1857–1933)

John Joly (Figure 1) was born on 1 November 1857 in County Offaly, Ireland (Nudds, 1996). After the sudden death of his father when he was still an infant, Joly, his mother and two elder brothers moved to Dublin, where he received his education at the celebrated Rathmines School, and later at 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 in the class. Soon afterwards he took up a position as assistant to the Professor of Engineering, and began his own researches on the density of gases, and the measurement of small pressures. At this time he invented the steam calorimeter for measuring the specific heat of minerals, which later played an important role in the kinetic theory of gases.

In 1891 Joly was appointed Assistant to the Professor of Natural and Experimental Philosophy (now known as Physics), and was in 1892 elected a Fellow of the Royal Society of London for his work on the specific heat of gases. Two years later he and his life-long friend Henry Dixon (later Professor of Botany at Trinity College, Dublin) published their seminal paper on the mechanism of the ascent of sap in plants. In 1895 a further product of his inventive mind and capabilities was his development of the first successful method of producing colour photographic images from a single plate; this was achieved by combining the three primary colours on to a single glass plate. The 'Joly Process' is still the basis of the method used in colour photography today.

In 1897 Joly succeeded William Sollas in the Chair of Geology and Mineralogy, a position he retained until his death in 1933. During his period of tenure he carried out valuable geological research in three areas. He made determinations of the age of the Earth using various methods (Wyse Jackson, 2001); he pioneered research on radioactivity and geology, which is the subject of this communication; and finally he introduced theories of global tectonics which he felt explained the nature of the Earth's surface features.

Joly was by all accounts a very popular man, and loved and respected by many. He was tall, with hair swept off his forehead, a bushy moustache, and spectacles perched on his nose. He spoke with what was considered to be a foreign accent. In reality his rolled r's were used to conceal a slight lisp (Dixon, 1941). For recreation he was a keen traveller and yachtsman — he owned several craft and learned to drive an automobile at an advanced age. He died on 8 December 1933 and was buried close to his beloved university at Mount Jerome Cemetery in Dublin.

John Joly was probably the finest scientist working in Ireland in the latter half of the nineteenth and first third of the twentieth centuries. He published nearly 270 papers and several books. He received medals from the Royal Dublin Society and the Geological Society of London, and received several honorary degrees from universities on both sides of the Atlantic. He was commemorated after his death by having a crater on Mars named in his honour.

Brief commentary on Joly's work on radioactivity and geology

Joly was a pioneer in the area of geology and radioactivity, but his contributions now tend to be overshadowed by those of others such as Arthur Holmes. Joly carried out much work calculating the radioactive content of terrestrial materials; he made valuable contributions in the area of global tectonics and its inter-relationship with the internal heat of the Earth; and he examined the age of the Earth from a number of perspectives. Although some of his ideas are now regarded as flawed, he nevertheless made enormous contributions to the geological debates at a time when new insights into the dynamics of the Earth were emerging. Joly's incisive and fertile mind was able to cope with highly complex ideas, which when allied with his brilliant numerical ability, yielded many notable publications.

In 1908 after a gap of thirty years the British Association for the Advancement of Science returned to Dublin. Within geological circles the discovery of the radioactive nature of uranium by Henri Becquerel in 1896 and radium by Marie Curie in 1898 had fired the imagination, so that by 1904 investigations were well underway to document the presence and amounts of radioactive materials in the Earth. By 1909 at least six radioactive elements had been discovered (Figure 2), although it was not recognised until later that many of these had daughter isotopes with different half-lives. The Honourable Robert J. Strutt (later Lord Rayleigh) is largely credited with the first reports of radioactive material in rocks in 1906, and similar evaluations were undertaken by Arthur Stewart Eve (1862–1941), an Englishman born in Ampthill, England, who worked at McGill University, Montreal, where he was Associate Professor of Mathematics and also Lecturer in Radioactivity. It was, however, their Irish contemporary, John Joly, who, for the next two decades, remained at the forefront of research on radioactivity and geology. From 1904 Joly carried out many analytical experiments to determine the radium and later thorium content of a variety of surface materials — lavas, deep-sea deposits, rocks derived from alpine tunnels, and sea-water, amongst others. For these experiments he and his research assistants (Arnold Lockhart Fletcher, until his early death in 1917 during hostilities in France, and later John Hewitt Jellett Poole, who was appointed Professor of Geophysics at Trinity College, Dublin in April 1934) devised their own equipment. In 1907 Joly demonstrated that pleochroic haloes in biotite within granite were produced by the

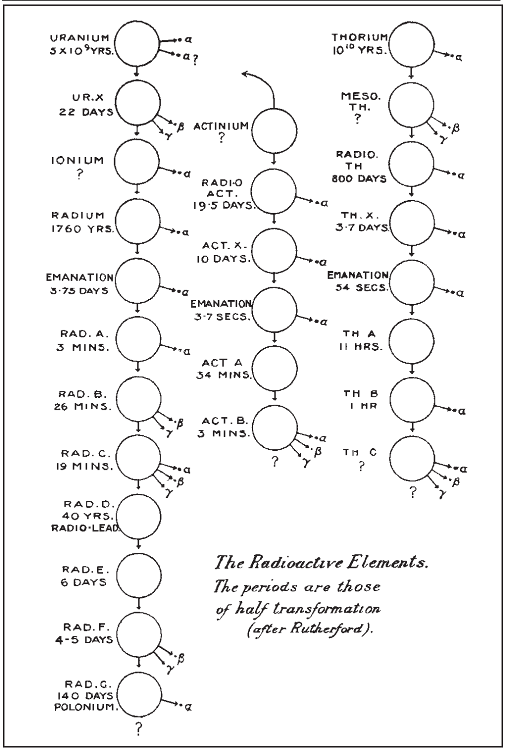

Figure 2 Radioactive elements and their decay sequences [From Joly 1909c].

breakdown of radioactive materials contained in tiny zircon crystals within the biotite crystals. Joly wrote extensively on haloes, and later with Ernest Rutherford utilised them to gauge the age of the Earth. From his work on haloes Joly was later to take a stance arguing that the rate of radioactive decay was not constant and had changed through the course of the planet's history. In this he was shown to be incorrect.

Many of Joly's results were published in a series of papers in *Philosophical Magazine*, of which he was editor, and he was able to present a synthesis of his thoughts on the subject in his Presidential Address to Section C (Geology) of the British Association for the Advancement of Science, delivered on 3 September, 1908. His views would have been well known to geologists and physicists on both sides of the Atlantic, as his address was published in three similar versions in 1908 and 1909: once in *Nature* (two days after the address) (Joly, 1908), once in the *Report of the British Association for the Advancement of Science* for 1908 (Joly, 1909a), and again in the *Smithsonian Report* for 1908 (Joly, 1909b). It was also expanded and supplemented with data from his publications in his book *Radioactivity and Geology*, also published in February 1909 (Joly 1909c), which was aimed at the general and scientific reader.

In the 1908 address Joly began to think about the effects of radioactive elements, particularly uranium, on the internal heat budget of the Earth. This vexed question had implications for the widely-held and widely-accepted ideas of Lord Kelvin, who advocated that the Earth was gradually cooling from its initial premordial temperature, and from this he calculated the age of the planet to be a maximum 40 million years old. As can be read in this account, Joly, along with others such as Ernest Rutherford, recognised that the radioactive elements within the Earth and indeed the Sun, contributed continual heat, so that the Earth was not cooling. While rejecting Kelvin's time-scale as being too low, even on the cooling evidence presented here Joly could not place the age of the Earth at greater than 100 million years old, as it would have been at odds with his own chronology based on the sodium content of the oceans.

Joly realised that the radiogenic heat influenced the surface expression of the rocks. In the early decades of the twentieth century Alfred Wegener's ideas on continental drift were assessed by geologists, some of whom rejected outright this theory, while others, including Joly, did not reject them out-of-hand, but suggested modifications to current ideas about global tectonics. Ultimately his thoughts led to his proposal of a series of thermal cycles popularised in his book *The Surface History of the Earth* (1925; 2nd edn 1930). He argued that the internal heat of the Earth built up over time, eventually melting the basaltic crustal horizons beneath the continental crust. In a thermal cycle molten magma then migrated from beneath the continental crust to beneath the thinner oceanic crust, and heat was lost into the oceans. Joly argued that the cooling of the melted lithosphere caused it to recrystallise and contract. This resulted in the generation of compressive forces which forced the oceanic crust to press against the margins of the continental crust, thereby initiating orogenesis or mountain building. Joly estimated that these 'revolutions', as they were called, took place once every 50 million years or so; and he was able to distinguish five or six such events. Joly's tectonic ideas were flawed. Nevertheless, he foresaw the driving force for continental drift, suggested by Arthur Holmes in 1925, to be the convection currents driven by the heat produced by the radioactive breakdown of elements within the Earth's interior.

It was perhaps Joly's willingness to exercise his imagination that allowed him to develop geological theories related to the fledgeling subject of radioactivity. He was also not afraid to devise some unusual experiments so as to try and derive data. It is interesting to read of one such scheme, whereby in the year before he died he experimented on himself to see what effect γ rays might have on his memory by inserting radioactive pads into the lining of his hat! Unfortunately he left no results of this experiment. Of all his research on radioactivity, he was most proud of that on radium, which led to his establishing the Irish Radium Institute in 1914 which exploited the medical uses of the radioactive element.

The following extracts from Joly's classic paper of 1908 are taken from the last version published in the *Smithsonian Report* (Joly, 1909b) rather than from those published in England, as it incorporates some corrections made by Joly to his original published text. It has been left largely as published, as the text is self-explanatory. A small number of interpolations and explanatory footnotes are provided. The original page numbers are given in parentheses. This paper has been selected as being representative of Joly's work and ideas on radioactivity and geology, particularly on radium and on the effect of uranium on the internal heat of the Earth. It encapsulated most of what was known at that time about the infant science of radioactivity and its bearing on geology (or radiogeology as it has become known). Although scientists other than Joly contributed to this debate, this paper can be considered a classic in this genre.

John Joly (1908): Uranium and Geology

[p. 355 of the original paper]

In our day but little time elapses between the discovery and its application. Our starting point is as recent as the year 1903, when Pierre Curie and [Albert] *Laborde showed experimentally that radium steadily maintains its temperature above its surroundings. As in the case of many other momentous discoveries, prediction and even calculation had preceded it. Rutherford and* [R.K.] *McClung, two years before the date of the experiment, had calculated the heat equivalent of the ionization effected by uranium, radium, and thorium. Even at this date (1903) there was much to go upon, and ideas as to the cosmic influence of radio-activity were not slow in spreading.*

I am sure that but few among those whom I am addressing have seen a thermometer rising under the influence of a few centigrams of a radium salt; but for those who pay due respect to the principles of thermodynamics, the mere fact that at any moment the gold leaves of the electroscope may be set in motion by a trace of radium, or, better still, the perpetual motion of Strutt's "radium clock," is all that is required as demonstration of the ceaseless outflow of energy attending the events proceeding within the atomic systems.

Although the term "ceaseless" is justified in comparison with our own span of existence, the radium clock will in point of fact run down and the heat outflow gradually diminish. Next year there will be less energy forthcoming to drive the clock, and less heat given off by the radium by about the one three-thousandth part of what now are evolved. As geologists, accustomed to deal with millions of years, we must conclude that these actions, so far from being ceaseless, are [p. 356] *ephemeral indeed, and that if importance is to be ascribed to radium as a geological agent we must seek to find if the radium now perishing off the earth is not made good by some more enduringly active substance.*

That uranium is the primary source of supply [of radium and hence of heat] *can not be regarded as a matter of inference only. The recent discovery of ionium*[1] *by* [Bertram] *Boltwood serves to link uranium and radium, and explains why it was that those who sought for radium as the immediate offspring of uranium found the latter apparently unproductive, the actual relation of uranium to radium being that of grandparent. But even were we without this connected knowledge, the fact of the invariable occurrence in nature of these elements, not only in association, but in a quantitative relationship, can only be explained on a genetic connection between the two. This evidence, mainly due to the work of Boltwood, when examined in detail, becomes overwhelmingly convincing.*

Thus it is to uranium that we look for the continuance of the supplies of radium[2]*. In it we find an all but eternal source. The fraction of this substance which decays each year, or, rather, is transformed to a lower atomic weight, is measured in tens of thousands of millionths; so that the uranium of the earth one hundred million years ago was hardly more than 1 per cent greater in mass than it is to-day.*

As radio-active investigations became more refined and extended, it was discovered that radium was widely diffused over the earth. The emanation [radon] *of it was obtained from the atmosphere, from the soil, from caves. It was extracted from well waters. Radium was found in brick-earths, and everywhere in rocks containing the least trace of demonstrable uranium, and Rutherford calculated that a quantity of radium so minute as* 4.6×10^{-14} *grams per gram of the earth's mass would compensate for all the heat now passing out through its surface as determined by the average temperature gradients. In 1906 the Hon. R. J. Strutt, to whom geology owes so much, not only here but in other lines of advance, was able to announce, from a systematic examination of rocks and minerals from various parts of the world, that the average quantity of radium per gram was many times in excess of what Rutherford estimated as adequate to account for terrestrial heat loss. The only inference possible was that the surface radium was not an indication of what was distributed throughout the mass of the earth, and, as you all know, Strutt suggested a world deriving its internal temperature from a radium jacket some 4 miles in thickness, the interior being free from radium.*

My own experimental work, began in 1904, was laid aside till after Mr. Strutt's paper had appeared, and a valued correspondence [p. 357] *with its distinguished author was permitted to me. This address will be concerned with the application of my results to questions of geological dynamics.*

Did time permit I would, indeed, like to dwell for a little on the practical aspect of measurements as yet so little used or understood; for the difficulties to be overcome are considerable and the precautions to be taken many. The quantities dealt with are astoundingly minute, and to extract with completeness a total of a few million millionths of a cubic millimeter of the radio-active gas — the emanation — from perhaps half a liter or more of a solution rich in dissolved substances can not be regarded as an operation exempt from possibility of error; and errors of deficiency are accordingly frequently met with[3]*. Special difficulties, too, arise when dealing with certain classes of rocks. For in some rocks the radium is not uniformly diffused, but is concentrated in radio-active substances. We are in these cases assailed with all the troubles which beset the assayer of gold who is at a loss to determine the average yield of a rock wherein the ore is sporadically distributed. In the case of radium determinations this difficulty may be so much the more intensified as the isolated quantities involved are the more minute and yet the more potent to affect the result of any one experiment. There is here a source of discrepancy in successive experiments upon those rocks in which, from metamorphic or other actions, a segregation of the uranium has taken place. With such rocks the divergences between successive results are often considerable, and only by multiplying the number of experiments can we hope to obtain fair indications of the average radioactivity. It is noteworthy that these variations do not, so far as my observations extend, present themselves when we deal with a recent marine sediment or with certain unaltered deposits wherein there has been no readjustment of the original fine state of subdivision, and even distribution, which attended the precipitation of the uranium in the process of sedimentation.*

But the difficulties attending the estimation of radium in rocks and other materials leave still a large balance of certainty—so far as the word is allowable when applied to the ever-widening views of science — upon which to base our deductions. The emanation of radium is most characteristic in behavior; knowledge of its peculiarities enables us to distinguish its presence in the electroscope, not only from the emanation of other radio-active elements but from any accidental leakage or inductive disturbance of the instrument. The method of measurement is purely comparative. The cardinal facts upon the strength of which we associate radium with geological dynamics, its development of heat, and its association with uranium are founded in the first ease directly on observation and in the second on evidence so [p. 358] *strong as to be equally convincing. Recent work on the question of the influence of conditions of extreme pressures*

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[1] Ionium is a natural radioactive isotope of thorium.

[2] There are 25 isotopes of radium in all, and four that occur in nature - ^{223}Ra, ^{224}Ra, ^{226}Ra and ^{228}Ra. These are produced by the decay of thorium or uranium: ^{238}U decays to ^{226}Ra. Radium (and its derivative gas radon) is considered a major health-hazard as it can become substituted for calcium in bones. In many buildings situated over crystalline rocks radon build-up in cellars and basements can constitute a health risk to the occupants.

[3] The radium content in rocks and other materials was measured by using a two-stage process of extraction and measurement. Firstly, the material was dissolved in two batches in both an alkaline and acidic solution, and allowed to stand in flasks for three weeks. Later the solution is boiled and the air and radon collected in a glass flask held above a condenser (Figure 3a), after which the gases are passed to an electroscope (Figure 3b). In this delicate instrument a thin brass strip is held in a tube of sulphur, and a narrow gold leaf attached to it. The brass strip is then electrified, which cases the gold leaf to diverge away from the brass strip at about 30˚. When the electroscope is discharged the gold leaf falls towards the brass strip and this can be calibrated. With the introduction of the radon this rate increases by about 30% to that normally seen, and the amount corresponds to the volume of radium originally present in the sample. Later in 1911 Joly devised another method in which the radon was derived by mixing the material to be analysed with sodium and potassium carbonates and heating in a fumace.towards the brass strip and this can be calibrated. With the introduction of the radon this rate increases by about 30% to that normally seen, and the amount corresponds to the volume of radium originally present in the sample. Later in 1911 Joly devised another method in which the radon was derived by mixing the material to be analysed with sodium and potassium carbonates and heating in a furnace].

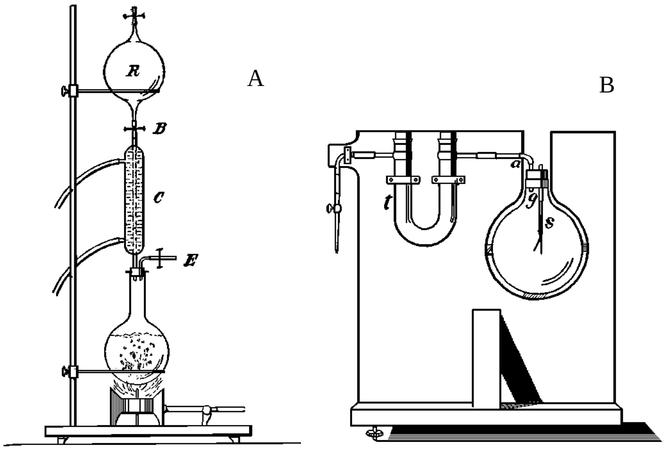

Figure 3 Equipment for measuring the amount of radium in terrestrial materials. a) Apparatus used to collect radon; b) The electroscope (s = sulphur tube below which hang the brass strip and at an angle, the gold leaf) [From Joly 1909c]

and temperatures on the radio-active properties of radium appear to show that, as would be anticipated, the effect is small, if indeed existent. As observed by [Walter] *Makower*[4] *and Rutherford, the small diminution noticed under very extreme conditions in the γ radiation possibly admits of explanation on indirect effects. These observations appear to leave us a free hand as regards radio-thermal effects, unless when we pursue speculations into the remoter depths of the earth, and even there, while they remain as a reservation, they by no means forbid us to go on.*

The precise quantity of heat to which radium gives rise, or, rather, which its presence entails, can not be said to be known to within a small percentage, for the thermal equivalent of the radio-active energy of uranium, actinium, and ionium, and of those members of the radium family which are slow in changing, has not been measured directly. Professor Rutherford has supplied me, however, with the calculated amount of the aggregate heat energy liberated per second by all these bodies. In the applications to which I shall presently have to refer I take his estimate of 5.6×10^{-2} *calories per second as the constant of heat production attending the presence of one gram of elemental radium.*

To these words of introduction I have to add the remark, perhaps obvious, that the full and ultimate analysis of the many geological questions arising out of the presence of radium in the earth's surface materials will require to be founded upon a broader basis than is afforded by even a few hundred experiments. The whole sequence of sediments has to be systematically examined; the various classes of igneous materials, more especially the successive ejecta of volcanoes, fully investigated. The conditions of entry of uranium into the oceanic deposits has to be studied, and observations on sea water and deep-sea sediments multiplied. All this work is for the future; as yet but little has been accomplished.

The radium in the rocks and in the ocean

The fact, first established by Strutt, that the radium distributed through the rock materials of the earth's surface greatly exceeds any permissible estimate of its internal radio-activity has not as yet received any explanation. It might indeed be truly said that the concentration of the heaviest element known to us (uranium) at the surface of the earth is just what we should not have expected. Yet a simple enough explanation may be at hand in the heat-producing capacity of that substance. If it was originally scattered through the earth-stuff, not in a uniform distribution but to some extent concentrated fortuitously in a manner depending on the origin of terrestrial ingredients [p. 359]*, then these radio-active nuclei heating and expanding beyond the capacity of surrounding materials would rise to the surface of a world in which convective actions were still possible, and, very conceivably, even after such conditions had ceased to be general; and in this way the surface materials would become richer than the interior. For instance, the extruded mass of the Deccan basalt would fill a sphere 36 miles in radius. Imagine such a sphere located originally somewhere deep beneath the surface of the earth surrounded by materials of like density. The ultimate excess of temperature, due to its uranium, attained at the central parts would amount to about 1,000˚C, or such lesser temperature as convective effects within the mass would permit. This might take some thirty million years to come about, but before so great an excess of temperature was reached the force of buoyancy developed in virtue of its thermal expansion must inevitably bring the entire mass to the surface. This reasoning would, at any rate, apply to material situated at a considerable distance inward, and may possibly be connected with vulcanicity and other crustal disturbances observed at the surface. The other view, that the addition of uranium to the earth was mainly an event subsequent to its formation in bulk, so that radio-active substances were added from without and, possibly, from a solar or cosmic source, has not the same àpriori probability in its favor.*

[In the next six pages of the original text Joly gives results of his many investigations into the radium content of various terrestrial materials.]

Uranium and the internal heat of the earth

[p.365] *While forced to deny of the earth's interior any such richness in radium as prevails near the surface, the inference that uranium exists yet in small quantities far down in the materials of the globe is highly probable. This view is supported by the presence of radium in meteoric substances and by its very probable presence in the sun—that greatest of meteorites. True, the radio-thermal theory can not be supposed to account for any great part of solar heat unless we are prepared to believe that a very large percentage of uranium can be present in the sun, and yet yield but feeble spectroscopic evidence of its existence. Taken all together, the case stands thus as regards the earth: We are assured of radium as a widely distributed surface material, and to such depths as we can penetrate. By inference from the presence of radium in meteoric substances and its very probable presence in the sun, from which the whole of terrestrial stuff probably originated, as well as by the inherent likelihood that every element at the surface is in some measure distributed throughout the entire mass, we arrive at the conclusion that radium is indeed a universal terrestrial constituent.*

[p. 366] *The dependent question then confronts us: Are we living on a world heated throughout by radio-thermal actions? This question one of the most interesting which has originated in the discovery that internal atomic changes may prove a source of heat—can only be answered (if it can be*

[4] Makower of the University of Manchester, was co-author of a useful book with Hans Geiger *Practical Measurements in Radio-activity,* 1912. This contained the first account of what became known as the Geiger Counter.

answered) by the facts of geological science.

I will not stop to discuss the evidence for and against a highly heated interior of the earth. I assume this heated interior the obvious and natural interpretation of a large class of geological phenomena, and pass on to consider certain limitations to our knowledge which have to be recognized before we are in a position to enter on the somewhat treacherous ground of hypotheses.

In the first place, we appear debarred from assuming that the surface and central interior of the earth are in thermal connection, for it seems certain that, since the remote period when (probable) convective effects became arrested by reason of increasing viscosity, the thermal relations of the surface and interior have become dependent solely on conductivity. From this it follows if the state of matter in the interior is such as Lord Kelvin assumed — that is, that the conductivity and specific heat may be inferred from the qualities of the surface materials — we must remain in thermal isolation from the great bulk of the interior for hundreds of millions of years, and perhaps even for more than a thousand million of years. Assuming a diffusivity similar to that of surface rocks, and starting with a temperature of 1000˚F., Kelvin found that after one thousand million years of cooling there would be no sensible change at a depth from the surface greater than 568 miles. In short, even if this great period — far beyond our estimates of geological time — has elapsed since the consistentior status, the cooling surface has as yet borrowed heat from only half the bulk of the earth.

It is possible, on the other hand, that the conductivity increases inward, as Professor Berry has contended; and if the central parts are more largely metallic this increase may be considerable. But we find ourselves here in the regions of the unknown.

With this limitation to our knowledge, the province of geothermal speculation is a somewhat disheartening one. Thus if with Rutherford, who first gave us a quantitative estimate of the kind, we say that such and such a quantity of radium per gram of the earth's mass would serve to account for the $2.6{\times}10^{20}$ *calories, which, according to the surface gradients, the earth is losing per annum, we can not be taken as advancing a theory of radio-active heating, but only a significant quantitative estimate. For, in fact, the heat emitted by radium in the interior may never have reached the surface since the convective conditions came to an end.*

And here, depending upon the physical limitations to our knowledge of the earth's interior, a possibility has to be faced. That [p. 367] *uranium is entirely absent from the interior is, as I have said, in the highest degree unlikely. If it is present, then the central parts of the earth are rising in temperature. This view, that the central interior is rising in temperature, is difficult to dispose of, although we can adduce the evidence of certain surface phenomena to show that the rise in temperature during geological time must be small or its effects in some manner kept under control. In a word, whether we assume that the whole heat loss of the earth is now being made good by radio-active heating or not, we find, on any probable value of the conductivity, a central core almost protected from loss by the immense mass of heated material interposed between it and the surface, and within this core very probably a continuous source of heat. It is hard to set aside any of the premises of this argument.*

We naturally ask, Whither does the conclusion lead us? We can take comfort in a possible innocuous outcome. The uranium itself, however slowly its energy is given up, is not everlasting. The decay of the parent substance is continually reducing the amount of heat which each year may be added to the earth's central materials. And the result may be that the accumulated heat will ultimately pass out at the surface by conductivity, during remote future times, and no physical disturbance result.

The second limitation to our hypotheses arises from this transformation and gradual disappearance of the uranium. And this limitation seems as destructive of definite geothermal theories as the first. To understand its significance requires a little consideration. The fraction of uranium decaying each year is vanishingly small, about the ten thousand-millionth part; but if the temperature of the earth is maintained by uranium and consequently its decay involves the fall in temperature of the whole earth, the quantity of heat escaping at the surface attendant on the minute decrement would be enormous. An analogy may help to make this clear. Consider the familiar case of a boiler maintained at a particular temperature by a furnace within. Let the combustion diminish and the furnace temperature fall a little. The whole mass of the boiler and its contents follow the downward movement of temperature, heat of capacity escaping at the surface. An observer, only noting the outflow of radiated heat and unable to observe the minute drop of temperature, would probably ascribe to the continued action of the furnace, heat which, although derived from it in the past, should no longer be regarded as indicating the heating value of the combustion. Magnify the boiler to terrestrial dimensions; the minutest fall in temperature of the entire mass involves immense quantities of heat passing out at [p. 368] *the surface, which no longer indicate the sustaining radio-thermal actions within.*

It is easy to see the nature of the difficulties in which we thus become involved. In fact, the heat escaping from the earth is not a measure of the radium in the earth, but necessarily includes, and for a great part may possibly be referred to, the falling temperature, which the decay of the uranium involves. If we take λ *(the fraction of uranium transforming each year) as approximately* 10^{-10} *and assume for the general mass of the earth a temperature of l,500˚, a specific heat of 0.2, and, taking* $6{\times}10^{27}$ *as its mass in grams, we have, on multiplying these values together, a loss in calories per annum of* $1.8{\times}10^{20}$*. This by hypothesis escapes at the surface. But the surface loss, as based on earth gradients of temperature, is but* $2.6{\times}10^{20}$ *calories. We are left with* $0.8{\times}10^{20}$ *calories as a measure of the radium present. On this allowance our theories, in whatever form, must be shaped. Nor does it appear as if relief from this restriction can be obtained in any other way than by denying to the interior parts of the earth the requisite high thermal conductivity. Taking refuge in this, we are, however, at once confronted with the possibility of internal stores of radium of which we know nothing, save that they can not, probably, be very great in amount. In short, I believe it will be admitted on full examination of this question that, while we very probably are isolated thermally from a considerable part of the earth's interior, the decay of the uranium must introduce a large subtractive correction upon our estimates of the limiting amounts of radium which might be present in the earth.*

But, finally, is there in all these difficulties sufficient to lead us to reject the view that the present loss of earth heat may be nearly or quite supplied by radium, and the future cooling of the earth controlled mainly by decay of the uranium? I do not think there are any good grounds for rejecting this view. Observe, it is the condition toward which every planetary body and every solar body containing stores of uranium must tend; and apparently must attain when the rate of loss of initial stores of heat, diminishing as the body grows colder, finally arrives at equilibrium with the radio-thermal supplies. This final state appears inevitable in every case unless the radioactive materials are so subordinate that they entirely perish before the original store of heat is exhausted.

Now, judging from the surface richness in radium of the earth and the present loss of terrestrial heat, it does not seem reasonable to assign a subordinate influence to radio-

thermal actions; and it appears not improbable that the earth has attained, or nearly attained, this final stage of cooling.

How, then, may we suppose the existing thermal state maintained? A uniformly radio-active surface layer possessing a basal temperature [p. 369] *in accordance with the requirements of geology is, I believe, not realizable on any probable estimate of the allowable radium, or on any concentration of it which my own experiments on igneous rocks would justify.*

But we may take refuge in a less definite statement, and assume a distribution by means of which the existing thermal state of the crust may be maintained. A specially rich surface layer we must recognize, but this need be no more than a very few miles deep; after which the balance of the radium may be supposed distributed to any depth with which we are thermally connected. Below that our knowledge is indefinite. The heat outflow at the surface is in part from the surface radium, in part due to the cooling arising from the diminishing amount of uranium, in part from the deep-seated radium. In this manner the isogeotherms are kept in their places, and a state is maintained which is in equilibrium with the thermal factors involved, but which can not be considered steady, using the word in a strictly accurate sense, in view of the decay of the uranium.

While the existing thermal state may, I think, thus be maintained by radio-active heating and radio-active decay, we find ourselves in considerable difficulties if we extend this view into the past and assume that the same could be said of any previous stage of the earth's history. If the heat emitted by the earth, when the surface was at melting temperature, was in a state of equilibrium with the radio-active supplies, then, at that date, there must have been many thousands of times the present amount of uranium on the earth, and the period of the consistentior status must be put back by thousands of millions of years. Apart from hopeless contradiction with every geological indication as to the age of the earth, difficulties in solar physics arise. For the sun must be supposed of equal duration, and we are required to assume impossible amounts of uranium to maintain its heat all that great lapse of time; and again this uranium would perish at just the same rate as that upon the earth, so that at the present time the solar mass must be, for by far the greater part, composed of inert materials of high atomic weight—the products of the transformations of the uranium family. The difficulty is best appreciated when we consider that even to maintain its present rate of heat loss by radium supplies, some 60 per cent of its mass must be composed of uranium. But there are other troubles to face if we adopt this view. The earth, or rather those parts of it which are sufficiently near the surface to lose heat at the requisite rate, would have cooled but 1 per cent in 10^8 *years. Shrinkage of the outer parts and crustal thickness will be proportionately small, and we must put back our epochs of mountain building to suit so slow a rate of cooling and shrinkage and refer the earlier events of the kind into a past of inconceivable remoteness. Otherwise we must abandon the only tenable* [p. 370] *theory of mountain formation with which we are acquainted. On such a time scale the ocean would be supersaturated under the influence of the prolonged denudation like the waters of certain salt lakes, and the sediments would have accumulated a hundredfold in thickness.*

Nor do the facts as we know them equire from us such sacrifices. We are not asked to raise these difficulties on supposititious quantities of uranium for the existence of which there is no evidence. Radium has occasioned no questioning of the older view that the cooling of the earth from a consistentior status has been mainly controlled by radiation. But, on the contrary, this new revelation of science has come to smooth over what difficulties attended the reconciliation of physical and geological evidence on the Kelvin hypothesis. It shows us how the advent of the present thermal state might be delayed and geological time lengthened, so that Kelvin's forty or fifty million years might be reconciled with the hundred million years which some of us hold to be the reading of the records of denudation.

On this more pacific view of the mission of radium to geology, what has been the history of the earth? In the earlier days of the earth's cooling the radiation loss was far in excess of the radiothermal heating. From this state by a continual convergence, the rate of radiation loss diminishing while the radio-thermal output remained comparatively constant, the existing distribution of temperature near the surface has been attained when the radio-thermal supply may nearly or quite balance the loss by radiation. The question of the possibility of final and perfect equilibrium between the two seems to involve the interior conductivity and in this way to evade analysis.

It will be asked if the facts of mountain building and earth shrinkage are rendered less reconcilable by this interference of uranium in the earth's physical history. I believe the answer will be in the negative. True, the greatest development of crustal wrinkling must have occurred in earlier times. This must be so, in some degree, on any hypothesis. The total shrinkage is, however, not the less because delayed by radio-thermal actions, and it is not hard to point to factors which will attend the more recent upraising of mountain chains tending to make them excel in magnitude those arising from the stresses in an earlier and thinner crust.

[Joly's text continues with a five page discussion of the effects of radioactivity on underground temperatures, much of which draws on his work on the rocks of the St Gothard and Simplon Tunnels driven through the Alps. He ends his text with a discussion of the effects of radioactive heat and the instability of the Earth's crust]

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