Relations of Radioactivity to Cosmogony and Geology[1]

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[For those who are only interested in reading the parts of this paper that are most relevant for the history of geology, please refer to the note at the end of this document.]

1 Introduction

Even during the progress of a campaign, when complete information is necessarily unattainable, it is well to assemble facts and probabilities in an orderly manner, and to make a review of the situation as a guide to further action. It is as yet far too early to pronounce finally upon the part which radioactivity will eventually play in cosmogonic theories, but not too early considering the bearing of recent discoveries on the genesis and past history of the globe. Since geologists to whom this paper is addressed can not be expected to be very familiar with radioactivity, I shall first make an attempt to sketch in outline such features of that subject as seem to me of especial interest to us; next I shall try to show under what conditions radioactive substances can come into existence, and finally discuss the geological effects which may be expected from them.

2 Outline of radioactivity

Investigations in radioactivity have developed out of the study of the cathode rays and the Roentgen rays, the properties of which amazed the world a dozen years ago. They were studied on the theoretical side by Mr Lorentz and Mr Larmor, and on the experimental as well as the theoretical side by Mr J. J. Thomson. These investigations have established that the atom is in fact extremely complex, consisting of corpuscles or electrons, which seem to have a constant mass from whatever substance they may be produced, this mass being about the one-thousandth part of that of an atom of hydrogen. The electrons always carry a negative charge of electricity. In an electrically neutral atom the electrons are in rapid, gyratory motion, the details of which are at least as complex as those of the planets in the solar system, and they are held together by a positive electric charge equal to the sum of the negative charges carried by the electrons. The electrons seem to have the same mass and charge as ions and to be identical with them.[2]

[1]Manuscript received by the Secretary of the Society April 1, 1908.
This paper was not read at the meeting or presented by title, but was offered for publication and accepted by a unanimous vote of the Publication Committee.

[2]J.J. Thomson: Electricity and matter, 1904.

This electronic theory of matter, which rests on a solid basis of experiment, almost implies the possibility of disintegrating atoms. To provide for atomic stability the electrons in the atom must describe orbits such that the system is absolutely conservative, losing no energy whatever. The smallest dissipation of energy must eventually lead to disruption.

In pursuing the study of the Roentgen rays the famous French physicist, Mr Henri Becquerel, accidentally discovered a new species of rays known by his name. The effect produced by the Becquerel rays is radio-activity. He made this discovery in experimenting with pitchblende, or impure uraninite, and at his suggestion the properties of this mineral were investigated by Mr and Mrs Curie, who detected in it the new element radium.

They found that this element was present in very minute amounts in pitchblende, and that it emitted Becquerel rays in vastly greater quantities than pitchblende or than uranium. This emission proved to be an atomic property, depending, not on the state of combination, but solely on the amount of the element present. With Laborde, Mrs Curie showed [3] that radium is continuously losing energy at an astonishing rate, so that one gram of radium would spontaneously raise the temperature of 100 grams of water one degree in one hour. Here, then is an actual case of an unstable atom undergoing resolution into something else, and therefore into at least two other atoms. In 1902 Messrs Rutherford and Soddy [4] suggested that helium might be one of the products, and in 1903 Messrs Ramsay and Soddy [5] demonstrated that helium was given off by radium bromide, thus for the first time proving the actual derivation of one element from another. Mrs Curie and Mr Dewar [6] made confirmatory experiments on radium chloride fused and sealed in a quartz glass tube. Helium was also shown by Mr Debierne [7] to be one of the products of the activity of actinium.

It was found that a series of different but analogous radioactive substances results from the breaking up of the radium atom, and the constant association of radium with uranium suggested that radium itself forms at the expense of uranium. These facts led Messrs Rutherford and Soddy in 1902 to their disintegration theory,[8] according to which "it is supposed that the atoms of radioactive bodies are unstable, and that a certain fixed proportion of them become unstable every second and break up with explosive violence, accompanied in general by the expulsion of particles." Of these the most important are called α particles and are regarded by most investigators as molecules of helium. They are expelled at tremendous velocities, the maximum being approximately 20,000 kilometers per second, about one-fifteenth of the velocity of light. Less important are the so-called β particles, which are electrons and have only about four-thousandth part of the mass of the α particles. They are emitted only by certain

[3] Comptes Rendus, vol. 136, 1903, p. 673.

[4] E. Rutherford: Radioactive transformation, 1906, p.181. This work has been my main authority in the preparation of these notes.

[5] Nature, vol. 68, 1903, p. 246.

[6] Comptes Rendus, vol. 138, 1904, p.190.

[7] Comptes Rednus, vol. 141, 1905, p.383.

[8] E. Rutherford: Radioactive transformation, 1906, p.14.

of the radioactive substances and have a velocity in some cases approaching that of light, but in spite of their velocity they possess far less energy than the helium atoms because of their minute mass. These β particles are identical with those which compose cathode rays. Of relatively small importance are the γ rays emitted by some radioactive substances. They are believed to be irregular disturbances of the ether identical in character with the Roentgen rays.

The heating effect produced by radioactive substances is almost entirely due to the dissipation of the energy of the α particles moving at the immense velocities already indicated. The excess of temperature of radium compounds above that of surrounding objects is a consequence of the arrest by other portions of the mass of α particles set free within the salt. The energy liberated by radioactive processes is of a wholly different order of magnitude from that of ordinary chemical chemical reactions. Thus the transformation of radium emanation is accompanied by nearly 4 million times as much heat as is given out by an equal volume of hydrogen and oxygen combining to form water.

The disintegration theory implies that there is a long series of products whose general formula might be written U — n He, where n is a whole number. Now the atomic weight of uranium is 238.5, the highest known, while that of helium is 4; so that if $n = 3$, the atomic weight would be 226.5. Mrs Curie's latest determination of the atomic weight of radium is 226.45; so that of radium fits perfectly into the theoretical series.

In uranium minerals radium, helium, and lead are always found together, and Mr Boltwood [9] suggested that lead was probably the stable, or relatively stable, end member of the series. If so, its atomic weight should be 206.5. It is really 206.9; but this small discrepancy may well be due to lack of precision in the atomic weight of helium, which is only inferred from its density. Very possibly it may be found that the best way of determining the atomic wight of helium is to divide the difference between the atomic weights of uranium and lead by 8, which would give He = 3.95. Lead has not yet been isolated from radium in appreciable quantities, but this is probably only because the quantity of radium itself available for experiment is almost infinitesimal.

According to the theory, there should be two radioactive substances yielding α particles intermediate between U and Ra and 4 between Ra and Pb. Just four products capable of emitting α particles are already known between Ra and Pb, but they have not been produced in sufficient quantities and pure enough to permit atomic weight determinations. Only one member between U and Ra has been discovered, and this, called ionium, was detected during the summer of 1907 by Mr. Boltwood. It is believed to be the immediate parent of radium or U — 2He. The missing link is represented by "uranium X", which emits β particles and γ rays, but no α particles capable of detection by present methods. It is considered probable that α particles may be given off from this substance, but at a velocity so low as not to ionize the gases through which they pass. In that case they would fail to affect the electrometer, which is the instrument employed to detect their presence.

[9] Philosophical Magazine, vol. 9, 1905, p.613.

The several members of the uranium lead series emit α particles at different characteristic velocities and their activities decay at different characteristic rates. The law of decay of any one of them is assuredly exponential, and observation tends to show that it is the simplest possible exponential; so that if I_t is the activity at time t, and I_o the activity at the epoch from which time is counted, while λ is a constant,

$$I_t = I_o \varepsilon.^{-\lambda t}$$

Here λ has a particular value for each radioactive substance. It follows that when

$$t = \log 2/\lambda = 0.6932/\lambda$$

the original activity is reduced to one-half and the time of reduction to this "half value" is conveniently used to define and identify the several substances.[10] For radium the half-value period is about 1,300 years, but for uranium it is computed at no less than 1,000 million years, and one of the products of the disintegration of radium (radium A) has a half value period of only 3 minutes.

The law of decay also leads to the conclusion that in the spontaneous decay of uranium a condition of radioactive equilibrium must eventually be reached in which each component radioactive substance decays just as fast as it is replenished. Considering helium and lead as the stable end products of the process of degeneration, Mr Rutherford points out that this should afford a means of determining the age of minerals. Helium indeed might escape in some cases, but he thinks lead would accumulate and afford an accurate measure of time. Mr Boltwood has more recently discussed a number of analyses on this basis, showing that the ratio of metallic lead to metallic uranium in a mineral multiplied by 10 million should give the age in years approximately. This hypothesis of course assumes that the law of decay is a true law of nature, not an approximation; that no chemical or physical conditions modify it, and that the mineral has been subject to no external attack by which either lead or uranium could be removed. It makes the further assumption that no lead compounds were soluble in the solutions from which the uranium minerals were deposited. I shall be obliged to recur to this subject.

Besides the uranium series, there are two other series of radioactive minerals the properties of which are less fully investigated. Thorium compounds, as Mrs Curie discovered, are radioactive and emit α particles which appear to have the same mass as the helium atoms expelled by radium.[11] The other end product of thorium degeneration is not certainly known, but the difference between the atomic weights of thorium and bismuth is just 24, which suggests that $\mathrm{Bi} + \mathrm{He}^6 = \mathrm{Th}$. If so, however, there is one

[10] The average life of a radioactive product is

$$\int_0^\infty \varepsilon^{-\lambda t} dt = 1/\lambda = 1.443 \times \text{half-value period.}$$

[11] Mr R. J. Strutt has recently described a mineral from Greenland which contains much thorium, but only a trace of radium, and gives off large quantities of helium. Chemical News, November 29, 1907.

undiscovered step in the process. Actinium also yields products which emit α particles, but the atomic weights of actinium is unknown. It is thought that it may be a sort of collateral descendant of uranium.

All three groups of radioactive bodies include remarkable substances, called *emanations*, which are of very great importance from the geological point of view. They are all gases which diffuse slowly into air and obey the ordinary law of gases. They are known as radium emanation, thorium emanation, and actinium emanation. These gases are not acted on to an appreciable extent by any chemical or physical agent, and Messrs Rutherford and Soddy have subjected radium and thorium emanations to treatment such that no gas excepting one of the argon-helium family could possibly have survived.

The three emanations thus belong to the group of inert gases, which also includes xenon, krypton, argon, neon, and helium, so that in all there are eight members of the group. According to the disintegration theory, all the emanations degenerate by losing successive atoms of helium and only in this manner. The analogies expressed by the periodic law, on the other hand, would lead to the expectation either that there should be other heavy inert gases, as yet unknown, which would break down by shedding off neon and argon,[12] or, as an alternative, that the known emanations should under certain conditions emit molecules of neon and argon. The former of these hypotheses would seem a priori less probable than the second, for no group is yet known to contain more than nine elements, while eight inert gases have already been discovered. On the other hand, the supposition that the emanations may emit other light inert gases besides helium would rob the theory of radioactivity of its wonderful simplicity. It could no longer be maintained that radioactivity proceeded irrespective of chemical or physical environment.

Now Mr A. T. Cameron and Sir William Ramsay [13] have recently published papers the conclusions of which are very novel and will not be generally accepted in toto until confirmed by others. They reach results of two kinds. They *incline* to believe that they have isolated lithium, and perhaps sodium, from copper salts by radioactive processes, and this is the conclusion which has attracted the most attention. To me it seems less fundamentally important and interesting than their unqualified assertion that under certain conditions argon and neon result from the degradation of radium emanation. When the emanation is dissolved in water they state that it yields almost exclusively neon, as its gaseous educt, while when a copper salt is simultaneously present in the solution, argon is the main product. As every one knows, Sir William was not only Lord Rayleigh's collaborator in the discovery of argon, but by himself identified terrestrial helium, and, with Mr Travers as collaborator, discovered neon, krypton, and xenon. With Mr Soddy, he was also the first to demonstrate that radium emits helium. By the methods which he developed the detection of neon and argon is not a matter of

[12] Mr R. J. Strutt regards it as possible that all the light inert gases have been produced by degeneration, but that only those which produce helium now survive. The Becquerel rays and the properties of radium, 1904, p.174.

[13] Journal of the Chemical Society, vol. 91, 1907, p. 1593

serious difficulty, and when he tells us that from water treated with radium emanation he got an uncondensable gas which gave a brilliant neon spectrum in which every line was identified by comparison with a vacuum tube containing atmospheric neon, there seems to be no room for doubt.[14] These chemists confirm once more the fact that radium emanation in an otherwise vacuous vessel, or when mixed with oxygen and hydrogen gases, yields helium as one of its products.

If argon and neon are produced under the conditions just mentioned, it would appear either that the α particles are of various kinds, according to circumstances, or that they are something different from molecules of the gaseous products. Messrs Cameron and Ramsay incline to the latter hypothesis, and suggest that the degradation of molecules of emanation is due to their bombardment by α particles, the disintegration being most complete and yielding helium under the simplest conditions, but less complete in the presence of water or copper salts, so that then heavier inert gases, argon and neon, result. This would leave the true nature of the α particles an open question. From its density and its probable position in the periodic series, Sir William thinks that radium emanation should be assigned an atomic weight of approximately 216.5.[15]

Another surprising feature of their investigation is a redetermination of the average life of radium from three experiments on the volume of emanation set free by radium bromide and radium sulphate. Their result is 236 years,[16] while Mr Rutherford, by a less direct method, obtained no less than 1,800 years.

It appears then that much remains to be done before even so brief a sketch of radioactivity as is here presented can be drawn without including uncertain features. Thus, for the present purpose, it must be considered how far facts of radioactivity which are undoubted bear upon geology. No one questions the enormous energy of radioactive transformations, which is also readily explained by the electronic theory of the atom, while the dissemination of radioactive substances in nature makes it essential for the geologist to reckon with the contribution to terrestrial heat which the dissipation of this energy involves.

Again, the gaseous nature of the emanations is indubitable, as well as that they are soluble in water, and thus a means is provided of transferring radioactivity from one geological formation to another almost without limit. The disintegration theory in its present shape can only be accepted with reserve until it is shown that Sir William Ramsay's neon and argon were not of radioactive origin, and the method which the disintegration theory affords of determining the age of minerals must be cautiously applied under checks by other methods. It seems highly probable that the "mineralizing" action of radioactive substances will be found extremely important, both in ore deposits and among a certain class of rocks.

[14] In this connection it is interesting to remember that the gases of the hot springs of Bath contain neon, the proportion of this gas being much greater than in the atmosphere.

[15] Journal of the Chemical Society, vol. 91, 1907, p. 931.

[16] Journal of the Chemical Society, vol. 91, 1907, p. 1282.

3 Origin of uranium and thorium

The discovery of radium surprised the world, but professional chemists were astonished rather at the special properties of the "element" than at the instability of an atom. It was, to be sure, pretty generally supposed by those who were without special knowledge of chemistry that the so-called elements were independent entities, but from the days of Lavoisier and Dalton philosophical chemists have declined to pin their faith to this idea. Lavoisier himself was familiar with "radicles," or groups of atoms, which enter into combination as if they were simple substances. Ammonium, the amids, and cyanogen are familiar examples; indeed, among organic substances compound radicles are not the exception, but the rule. If elements could combine to groups which behaved like simple substances, it necessarily followed that the chemical relations of elements were not distinctive, and that substances as yet unresolved might prove complex. The idea of a fundamental relationship among the elements first gained prominence in 1815, though Prout's hypothesis, namely, that all the atomic weights were multiples of that of hydrogen, which almost amounted to assuming that hydrogen was Roger Bacon's "protyle," [17] Urstoff, the one truly simple substance. Many of the great series of atomic weight determinations made during the first half of the nineteenth century were undertaken with the express purpose of testing Prout's hypothesis. They disproved it, but the idea of protyle did not die. In 1851 J. Dumas [18] boldly asserted his belief in the transmutability of metals and metalloids, basing his opinion largely upon the analogous character of triads and other groups of elements. The hypothesis was not favorably received by Faraday, Grove, and W. R. Gladstone, who partook in the discussion.

Various attempts at grouping the elements finally resulted in Mendeléf's famous periodic law (1869), which enabled its author successfully to predict the properties of unknown elements (gallium, scandium, germanium) and is now everywhere received as expressing true relationships between their various fundamental properties. Such relationships would of course be inconceivable, were the "simple substances" totally independent entities.

Great attention has been exited by Sir Norman Lockyer's hypothesis, published in December, 1873. He suggested that the elements might be dissociated by heat. "On this working hypothesis," he writes, "the so-called elements not present in the reversing layer of a star will be in course of formation in the coronal atmosphere and in course of destruction as their vapor density carries them down." His hypothesis supposes the original atoms of which a star is composed to be possessed of the additional potential energy of combination, or that they are endothermic compounds, and he points out that the liberation of this energy through dissociation would prolong the period during which the star would give light.[19] Lockyer thus begins nebular history with complex atoms. He made no attempt to explain under what conditions they formed or whence

[17] This term was revived by Sir William Crookes. Proceedings of the Royal Institution, 1887, vol. 12, p. 37.

[18] An address delivered at the Ipswich meeting of the British Association for the Advancement of Science, but not included in the report. See American Journal of Science, vol. 12, 1851, p. 275.

[19] Nature, vol. 9, 1894, pp. 411 and 429. Philosophical Transactions, vol. 164, 1874, p. 492.

they derived their internal energy. His hypothesis has always aroused interest, but, as C. A. Young put it, "is encumbered with great difficulties and has not yet been accepted by physicists and chemists."

In January, 1873, nearly a year before Sir Norman Lockyer's lecture, Mr F. W. Clarke was daring enough to suggest the possibility of the evolution of elements. "We do not know but that the evolution of one element from another may be possible," he wrote. "These elements which seem today so diverse in character may be, after all, one in essence. Upon this theory the planets should contain more elements than the sun; the sun more than some of the more advanced among the fixed stars, and these in turn should be more highly organized than the nebulæ."[20] Mr Clarke's hypothesis has not attracted much notice, but it is entirely in line with modern results. Thus Mr J. J. Thomson, in his Silliman lectures, 1904, said in discussing the electronic theory of matter:

> "If we regard the systems containing different numbers of units as corresponding to the different chemical elements, then as the universe gets older elements of higher and higher atomic weight may be expected to appear. Their appearance, however, will not involve the annihilation of the elements of lower atomic weight."[21]

Since 1873, as every one knows, great strides have been made in celestial spectroscopy, largely in consequence of Rowland's invention of concave gratings. It is therefore interesting to inquire the bearing of our present knowledge of the distribution of elements on the hypothesis of their evolution. It has occurred to me that the information available can be most instructively and compendiously conveyed by the help of the periodic system, as in the following table, where the cosmic distribution of the elements, arranged according to Mendeléef's classification, is indicated by typographical devices:

[20] Popular Science Monthly, vol. 2, 1873, p. 320. For this paper Clarke was roundly denounced by a distinguished analyst, being classed with dreamers and speculators like Charles Darwin. American Association for the Advancement of Science, 1874, p. 13.

[21] Electricity and matter, 1904, p. 103.

Classification of the Elements by the periodic System and their cosmic Distribution

Series.	0.	I.	II.	III.	IV.	V.	VI.	VII.	VIII.
1...	...	H‴-	...	...	...	...	...	...	...
2...	He‴-	Li-	Gl′	B	C′-	N″-	O″	F	...
3...	Ne	Na″-	Mg″-	Al′-	Si″-	P-	S-	Cl-	...
4...	A	K′-	Ca″-	Sc′	Ti″-	V″	Cr′-	Mn′-	Fe″-,Ni′-,Co′-
5...	...	Cu′-	Zn′	Ga″	Ge′	As-	Se	Br	...
6...	Kr	Rb	Sr′	Y′	Zr′	Cb	Mo′	...	Ru′, Rh′, Pd′
7...	...	Ag′	Cd′	In	Sn′-	Sb-	Te	I	...
8...	Xe	Cs	Ba″	La′	Ce′	...	...	...	...
9...	...	...	...	...	...	...	...	...	...
10...	...	...	...	...	...	Ta	W	...	Os, Ir, Pt
11...	...	Au	Hg	Tl	Pb′	Bi	...	...	...
12...	...	...	Ra	...	Th	U	...	...	...

All of the elements whose symbols are accented occur in the sun; those whose symbols have two accents have been detected in the stars of the Sirian class or the helium class. Three accents indicate components of nebulæ. The elements whose symbols are followed by a hyphen are found in meteorites.

A few comments must be made on the sources of information recorded in the table. In the gaseous nebula only helium, hydrogen, and nebulium have been detected. This last gas is unknown on earth or in the stars, but it is believed to be heavier than hydrogen (A. M. Clerke: Problems of astrophysics, p. 476). The list of elements in the helium stars and hydrogen stars includes all those which Miss Clerke regarded as well established, but chromium and nickel are perhaps present (ibid., p. 198). The identification of the solar elements rests chiefly on Rowland's great table of the solar spectrum, 1895 to 1897. In 1891 Rowland published a preliminary table (Johns Hopkins University circular) containing most of the elements enumerated in this paper. In the six succeeding years he was able to add only two, namely, platinum and ruthenium. Of these, platinum is represented by only one line (2,923.180), which it shares with cerium, and this seems to me insufficient evidence of platinum in the sun; but ruthenium has five lines, of which one is doubtful. Columbium (or niobium) appeared in the first list, but in the great table is represented by a single doubtful line with a wave length of 4,232.111, and I have left it out. Rowland photographed the spectrum of every element known in 1895 for comparison with the solar spectrum, excepting gallium, of which he had no specimen, and he failed to find even a doubtful trace of uranium or thorium. Mr P. G. Nutting has also been good enough to compare for me Exner and Haschek's table of the spectrum of uranium with a 30-foot reproduction of the solar spectrum, and finds no evidence of its existence. Rowland also found erbium and neodymium in the sun, but they do not appear in the table because their position in the periodic system is uncertain. Rowland did not include nitrogen in his lists, but seems to have agreed with other spectroscopists that the solar carbon lines are due to cyanogen. These lines consequently prove nitrogen just as well as carbon (Kayser and Runge,

Wiedemann's Annalen, vol. 38, 1889, p. 80). Since Rowland's labors closed, gallium has been found in the solar spectrum by Messrs Hartley and Ramage, the presence of oxygen was established by Messrs Runge and Paschen, and Sir William Ramsay has identified helium in clevite. Very lately the rare element, europium, has been identified by Mr J. Lunt (Proceedings of the Royal Society, series A, vol. 79, 1907, p. 118). Coronium has also been identified in the corona of the sun (Astrophysical Journal, vol. 10, 1899, p. 306), and is believed to be a very light inert gas. It is unknown on earth or in the stars. The list of elements in meteors is that given by Sir Archibald Geikie, with the addition of helium (Young's Astronomy). Some other simple substances (lead, silver, gallium) have been announced as determinable spectroscopically in meteorites, but spectroscopic traces in an accessible substance do not seem to compare with stellar constituents observed under conditions of very much greater difficulty.

Rowland's determinations of wave lengths have been shown by Mr Kayser to be less accurate than he supposed them (Philosophical Magazine, vol. 8, 1904, p. 568), but his identifications of the elements in the sun were made by direct comparison between photographs of the solar spectrum and of the spectra of the elements, and will presumably prove correct.

In the nebulæ only helium, hydrogen, and nebulium have been identified. Nebulium which in the earlier days of spectroscopy was confounded with nitrogen, does not appear in the table, because it has not been found on earth and its place in the periodic system is unknown. The nebulæ very likely contain other elements besides the three just mentioned, but the nebulæ are excessively tenuous bodies and must also be extremely cold, so that the simplicity of their spectra is not surprising.[22] Their luminosity is really as small as it appears, and few of them would be visible to the human eye, even if they were as close to us as the moon is. Langley determined the luminosity of the Owl nebula at a four-millionth part of that of white-hot iron. The origin of their light is uncertain. The glow may be due to electrical discharges, and thus analogous to the light produced in highly exhausted tubes of hydrogen at the temperature of liquid air, or possibly it is some unknown variety of phosphorescence. Though from association we incline to infer a high temperature when luminosity makes its appearance, the aurora of the Arctic night affords an instance of a glow vastly brighter than that of any nebula, and at the very low temperature which prevails at altitudes of some 34 miles. There is no proof that the gaseous nebulæ are devoid of solid matter, while it is strongly suspected that the white nebulæ do contain solids.

There does not seem to be the least doubt that stars are developed from nebulæ. The "helium" stars often have nebulous appurtenances and show significant spectral relations to the gaseous nebulæ. Helium stars pass by the finest gradations into hydrogen stars of the Sirian type, and these again into solar stars.[23]

In the table the known components of helium and Sirian stars, other than helium and hydrogen, are marked by two accents, and it is interesting to observe their distribution with reference to the periodic law. If a straight line be drawn from barium

[22] Cf. A. M. Clerke: Problems of astrophysics, 1903, p. 535.
[23] A. M. Clerke: Problems of astrophysics, 1903, p. 272.

to iron, not a single element below the line is found in nebulæ or the two groups of stars, and of all the elements identified in these celestial bodies barium has the highest atomic weight (137.4). About a third of the elements in or above this line are found in these stars. Doubtless more stellar elements will be detected as spectroscopic research advances, but it seems probable that the additional elements will have atomic weights below that of barium rather than above it.

The chief components of the sun are shown in the table by one or more accents. A few rare earths detected in its spectrum are omitted because their positions in the periodic law are as yet unknown. It is highly probable that some of the metalloids, as suphur and chlorine, may exist in the sun, although they are not spectroscopically evident. Even in the laboratory the spectra of the metalloids are very much obscured when metals are present in abundance. Of the 13 elements included in the last three series of the table, lead [24] alone is certainly found in the sun. The presence of helium and lead, considered in connection with the absence of uranium, is extremely suggestive.

Meteors bring to the earth matter most of which, at all events, belongs to the solar system; it is in part of cometary origin and in all probability resembles the raw material of which the earth is built up. In the table of the elements identified gravimetrically in meteorites are indicated by hyphens. Of these a few are not found in the sun or stars, namely, phosphorus, sulphur, chlorine, arsenic, antimony, and lithium. Meteorites must reach the sun, and the absence of lithium lines from the solar spectrum is surprising. Many of the elements of high atomic weight are also absent from the meteorites, or are present in quantities so small as to escape chemical analysis—all of those, in fact, whose atomic weights exceed those of antimony (120).

The plausibility of the evolution hypothesis is increased rather than diminished by the spectroscopic investigations of the last 35 years, and the relations of the cosmic distribution of elements to the periodic law add force to the suggestion. There is room in the table for just one very light, inert, or nullivalent element with an atomic weight below that of hydrogen. Possibly this protylic gas may be coronium. Assuming its existence, the facts known seem to point to an orderly and gradual development of members of the higher groups and the higher series.

The results of the electronic theory of matter add greatly to the force of the suggestion, as is apparent from the conclusion of Mr J. J. Thomson quoted above.

Radioactive phenomena strengthen the evidence immensely. Since it is now an established fact that some atoms can be resolved into at least two others, it can not be denied that under appropriate conditions the process might be reversed. This is recognized by Mr Rutherford, who considers it reasonable to suppose that under some circumstances heavy atoms were built up from the lighter and more elementary substances.[25]

These several lines of evidence shift the burden of proof from those who maintained the probability of evolution to the shoulders of those who deny it. Uranium and thorium

[24] In Rowland's list of 1891 lead had but one line. In the great table, however, it has two unquestioned lines and two questionable lines.

[25] Radioactive transformations, p. 194.

have not been detected in the stars or the sun, even with the most powerful modern apparatus and under special scrutiny; yet in the sun numerous allied elements very rare on the earth have been identified, including cerium, lanthanum, neodymium, erbium, and europium. It seems highly improbable that if uranium and thorium existed in any quantity in the sun their spectra should fail to appear. When the reasonableness of the evolution hypothesis is considered, this evidence of the absence of the radioactive elements from the sun is not merely negative. The probabilities are that these elements are built up, say from lead and helium, only in cooling stars or in planetary masses.

If uranium is assumed to be present in the stars and nebulæ, the mystery of the universe is portentiously increased. Regarding uranium as compounded of lead and helium, it is substantially inevitable to suppose that it was formed under conditions in which it was stable. The only alternative is to imagine it an evanescent product of the spontaneous decomposition of still heavier atoms and then it must be assumed that these were stable. Now $Pb.He_8$ is an endothermic compound and almost incomparably more endothermic than any other except its fellow members of the radioactive group. Its genesis, therefore, was accompanied by the absorption of a vast amount of energy locally concentrated and thus of great intensity. The cold and tenuous, gaseous nebulæ, whose density is less than that of the best laboratory vacuum, afford no mechanism for such a process. Uranium in the nebulæ would point to a precedent condensation, to a regeneration of the nebulous state from an aged solar system, such as was imagined by Immanuel Kant.[26] But such a process stands in conflict with the second law of dynamics and implies that the system is a *perpetuum mobile*. Only the discovery of fundamental laws of physics of which there is as yet no inkling would suffice to explain the presence of uranium in nebulæ.

It is the effort of science to reduce the facts of nature to their simplest expression. "From the earliest times there has been a tendency to regard varieties of matter as derivative,"[27] and to seek their origin in an undifferentiated protylic substance or Urstoff, as Kant called it. It is hardly possible to think of a truly primitive nebula otherwise than as composed of protyle. From the modern point of view, the atoms of this substance would be the simplest systems of corpuscles capable of stable equilibrium, and it is not impossible that coronium satisfies this definition.

There is thus, so far as I can see, neither direct evidence that the sun is a radioactive body, nor is the hypothesis that it is radioactive inherently probable. There is also very little evidence that the meteors are radioactive. Mr L. J. Strutt [28] found substantially no radioactivity in siderites. Some of the stony meteorites show activity, but they are not known to contain uranium and thorium minerals and may well have acquired their activity from terrestrial emanations.

On earth the crystallized uranium and thorium minerals are confined, so far as is known, to the pegmatic modifications of the granitic and syenitic rocks. The pitchblende of ore veins is not crystallized and is in all probability derived from the peg-

[26] Kant's Werke, Hartenstein, Leipzig, vol. 1, 1868, p. 302.
[27] A. M. Clerke : Modern cosmogonies, 1905, p. 148.
[28] Proceedings of the Royal Society, series A, vol. 77, 1906, p. 472.

matites by a secondary process. No andesites, basalts, peridotites, etcetera, have been found to carry uranium in weighable quantities, and there is much evidence that when freshly erupted they are not considerably radioactive.[29] Old ejecta, especially when porous, seem quite as active as average superficial rocks. That mediosilicic and subsilicic rocks at or near the surface of the earth and overlying or adjoining granitic rocks should acquire radioactivity from emanations and solutions is entirely intelligible.

Since uranium must have been stable when the minerals of which it is a chief component crystallized, the genesis of uranium must be possible under the conditions which accompany the formation of pegmatites. Now of these we know something. At a pressure of one atmosphere, silica crystalizes as quarts only below 800° centigrade, as was shown by Messrs Day and Shepherd,[30] and Mr Mügge [31] has recently demonstrated by a new and brilliant method that the dihexahedral quarts of pegmatites could form under ordinary pressure only above 570° centigrade. Facts presented by Mr Brögger also show that granitic and syenitic rocks have formed in many cases at depths of only a few hundred meters from the surface,[32] and in any case the granitic massives, with their effusive modifications, being the least dense of rocks, are relatively superficial. These data would indicate that at temperatures of less than 1000° combined with pressures of a hundred of more kilograms per square centimeter, uranium might form under proper chemical conditions. It may therefore yet prove possible to combine lead and helium in bombs, even though neither high temperatures nor great pressures alone suffice to arrest the disintegration of radioactive substances. The attempt should be made.[33]

4 Radioactivity and the earth's age

Much the most important aspect of radioactivity is its bearing on the age of the earth. It is very plausibly held that the observed increment in underground temperatures must be due in part, and may be due in great part, to this cause. In fact it has been established that a relatively thin layer of rock possessing the average radioactivity of surface rocks would suffice to maintain the observed temperature gradients indefinitely. This line of reasoning is in part supported by the discrepancy which has hitherto existed between the age of a cooling globe as found by Kelvin's application of Fourier's method and the antiquity of the ocean as is found from geological observations.

Supposing the uniform initial temperature of the globe and the thermal diffusivity of its substance known, the age by Kelvin's solution is inversely proportional to the

[29] Nasini and Levi: Accad. Lincei. Rendiconti, vol. 15, 1906, p. 391, and O. Scarpa, idem, vol. 16, 1907, p. 44.

[30] American Journal of Science, vol. 22, 1906, p. 276.

[31] Neues Jahrbuch für Mineralogie, 1907.

[32] Die Mineralien der Syenitpegmatitgaenge, 1890, p. 224.

[33] Since this section of this paper was completed and communicated to colleagues, an important paper on the evolution and devolution of the elements, by Messrs A. C. and A. E. Jessup, has appeared in the Philosophical Magazine for January, 1908. In it the periodic law has been employed in somewhat the same way as here. I print my reflections without change, as an independent contribution to the subject.

square of the surface temperature gradient. If the age were accurately known from independent geological observations, the corresponding gradient for a cooling globe could be inferred at once, and a comparison of this with the observed gradients would show in how far the theory of cooling fails to explain the facts. A brief review of the age determinations, however, will show that they lack the precision requisite to give such a comparison value as a means of determining the part played by radioactivity.

During the last 15 or 20 years much work has been expended upon geological estimates of the duration of post-Archean time. The accumulation of strata is a gradual process proceeding *pari passu* with the degradation of land surfaces, though greatly affected by local conditions; and had we the assurance that the maximum rate of accumulation in the past were the same as the maximum rate at present, fairly accurate results would be attainable. The formations have also been studied with especial view to the rate of deposition, a variation in which might manifest itself in a number of ways. The studies referred to, however, have not disclosed any indication that the limits of variation with time are great, and to a certain extent they have been allowed for by Mr Walcott,[34] whose discussion of the data is more minute and comprehensive than any other with which I have met. In 1893 he reached the conclusion that the minimum estimate for post-Archean time is 25 to 30 million years, the maximum 60 to 70 million years, and that 45 million years is the most probable. By a similar method Mr de Lapparent [35] in 1890 had estimated 67 to 90 million. In 1899 Sir Archibald Geikie [36] stated that, so far as he was able to form an opinion, 100 million years would suffice for the formation of stratified rocks, and in 1900 Mr Sollas [37] arrived at $26^1/_2$ million, assuming a constant rate of deposition. On the other hand, Mr Mellard Reade,[38] taking a low rate for erosion, computed a period of 95 million years since the base of the Cambrian. All of these estimates may have been chosen more or less unconsciously influenced by Kelvin's great paper on the secular cooling of the earth, which appeared in 1862. In 1860, however, John Phillips [39] estimated that the time required for the deposition of the stratified rocks lay between 38 and 96 million years.

As the figures themselves show, the uncertainty is great, because the data are imperfect; but the premises have been derived from different regions in different ways, and the conclusion seems fairly well established that a few tens of millions of years will cover the period of sedimentation.

A radically different and very important method is due to Mr Joly, who sought to determine the age of the ocean from its sodium content on the hypothesis that this

[34] Journal of Geology, vol. 1, 1893, p. 675.

[35] Bulletin Société de Géologie de France, vol. 18, 1890, p. 351.

[36] British Association for the Advancement of Science, 1899, p. 727.

[37] British Association for the Advancement of Science, 1900, p. 711.

[38] Geological Magazine, vol. 10, 1893, p. 99.

[39] "Life on the earth," etcetera, 1860, p. 119. I have checked the computation. Mr Reade, in his "Evolution of the earth's structure," 1903, p. 256, is somewhat severe on Phillips for stating in his "Treatise on geology," 1839, that the average wastage in the drainage basin of the Ganges is 1/40,000 yard, which he is quoted as saying is about 1/111 of an inch. In the U. S. Geological Survey's copy of the treatise, 12mo edition, undated, but catalogued as 1837-39, the fraction given is 1/4,000 yard, and this is about 1/111 inch. The 40,000 in Mr Reade's copy is merely a misprint for 4,000.

is derived at a uniform rate from the decomposition of the rocks of the land surface. In 1899 [40] Mr Joly reached 80 to 90 million years by his method, and in 1900 [41] he increased this estimate by 10 million in the course of an answer to a criticism by Mr Sollas,[42] who still thinks Joly's estimate too large by 30 or 40 million years. In 1902 Mr Mackie [43] discussed the same method in much detail. He appears to me to succeed in showing that Mr Joly's estimate is too large, and himself reaches 25 million without as, I think, justifying so great a reduction. Data are now accumulating on the composition of waters, and it will son be practicable to apply Mr. Joly's method more satisfactorily than was possible in 1900.[44]

It is noteworthy that the estimates from sedimentation (with a single exception) and those from oceanic sodium content vary between substantially the same limits, 25 to 100 million years—wide limits truly, but better than unlimited guesses.

Years ago biologists were inclined to claim vast periods of time in which to accomplish the evolution of species, but recent investigations seem to have convinced them that the rate of evolution even today is far from uniform, depending on the environment, and furnishes no safe guide to the lapse of time. Such studies as those of Mr de Vries on plants and of Mr Weldon on crabs show that under some circumstances specific modulation may be very rapid. Mr Walcott and Mr Sollas speak with authority, both as biologists and stratigraphers, and each expresses the conviction that his estimate from the strata is not consistent with the life record.

It would appear, then, that geology points to an age of the ocean which probably lies somewhere between 50 and 75 million years. For such a period there is also physical evidence wholly independent of the origin of the heat of the solar system. Sir George Darwin's studies of the earth-moon system led him to believe that the two planets parted company something over 54 million years ago.[45]

The age of the earth, considered as a cooling body, was computed by Clarence King,[46] using Kelvin's formulas under restrictions established by Mr Barus, at 24 million years, and this result was accepted by Kelvin [47] in his last paper on this great subject. The uniform initial temperature of this earth was 1,950° centigrade.

No one, I fancy, will be inclined to deny that the earth really is a cooling body of nebulous origin, and that a part of its heat is due to compression. Kant [48] in 1785 was

[40] Transactions of the Royal Society of Dublin, vol. 7, 1899, p. 23.

[41] British Association for the Advancement of Science, 1900, p. 369.

[42] Mr Sollas repeats his criticism in his volume, "The age of the earth," etcetera, 1905.

[43] Transactions of the Edinburgh Geological Society, vol. 8, 1902, p. 240.

[44] Cf. Mr F. W. Clarke's "Data of geochemistry." U. S. Geological Survey Bulletin no. 330, 1908, p. 110.

[45] Philosophical Transactions, vol. 170, 1879, p. 511, and vol. 171, 1880, p. 882.

[46] American Journal of Science, vol. 45, 1893, p. 1.

[47] Transactions of the Victoria Institute, vol. 31, 1899, p. 11.

[48] "Die Vulcane im Monde," 1785. The earliest expression of great ideas is always a matter of interest, and I therefore translate some passages of Kant's paper : "Whence came the original heat? . . . Whence came the heat of the sun? If it is assumed (as is probable, on other grounds) that the protyle of celestial bodies was originally distributed in a vaporous state throughout the whole space in which they now move, and that they have formed according to natural laws, as first by chemical affinity, but afterwards

the first to refer the heat of stellar bodies to the compression of nebulous matter, and Helmholtz [49] in 1854 was able to deal further with the subject, quantitatively in part, thanks to Joule's determination of the mechanical equivalent of heat. Once this cause of high temperatures was pointed out, its importance could not and can not be denied.

On reviewing the papers dealing with the earth as a cooling body, however, I must confess to find them unsatisfactory. The assumption of uniform initial temperature made by Kelvin seems to me untenable, because it leads either to earths which are tidally unstable for vast periods of time or to earths so cool that there was no fusion at all and no rearrangement of terrestrial matter by density. I have therefore investigated a somewhat more general problem,[50] the cooling of an earth in which the initial temperature increases directly as distance from the surface. The original surface temperature is supposed to be about that of the hottest recent lavas, say 1,300°, while on the basis of Mr Barus's experiments on diabase, the initial temperature at 40 miles from the surface is estimated at 1,600°. A discussion of the level of isostatic compensation, determined by Messrs Tittmann and Hayford,[51] leads to the belief that at a distance of 71 miles, or 114 kilometers, from the surface of the rock temperature most closely approaches its melting point. Finally, the diffusivity is taken as that of the Calton Hill trap investigated by Forbes and Kelvin. These data lead to an earth which has been solid throughout from the moment when the surface first conjealed; it is about 60 million years old, and the present surface gradient should be 1° Fahrenheit in 77 feet (1° centigrade in 42.2 meters). This gradient seems very low; but many still lower gradients are known, and whether it is too low to be acceptable is a matter for consideration.[52] It will be observed that in this method of dealing with the problem the age is not dependent, as it is in Kelvin's solution, on the present surface gradient temperature. The gradient here is a deduction. Since, also, the age found is in fairly good accord with the ages reached by other methods, my result for gradient is available

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and chiefly in obedience to universal attraction, then [Aldair] Crawford's discovery points the way to a comprehension of how any temperature you please might be produced simultaneously with the genesis of celestial bodies. . . . If, as he proves, matter expanded in vapor contains far more heat, and indeed, to maintain its expansion, requires far more heat, than when condensed—in other words, when nebulous matter is compressed to stellar bodies—then the resulting globes must contain more caloric than would suffice to maintain the natural equilibrium with the caloric of surrounding space." He goes on to explain that the amount of heat generated must be a direct function of the mass of the stellar body, and adds: "In this way we should comprehend why the central body, as that of greatest mass in any system, may be the hottest, and so in every case a sun."

[49] Die Wechelwirkung der Wissenschaften, 1854.

[50] Science, vol. 27, 1908, p. 227. In this paper, by an error in copying from the rough draft, the level of isostatic compression is stated as 71 miles, or 140 kilometers. The last figure should be 114. The proper value was used in the formulas and computations.

[51] Report to general conference of the International Geodetic Association, Washington, 1906.

[52] In my solution the curvature of the earth's surface is neglected. As is well known, Mr R. S. Woodward has discussed both the free and the conditioned cooling of a sphere initially at a uniform temperature ("Annals of mathematics," vol. 3, 1887, pp. 75 and 129). Excepting for ages of thousands of millions of years, his formulas applied to the earth give the same results whether the cooling is free or conditioned. I have compared his formula and Kelvin's for a 60×10^6 year earth initially at 1307° having the diffusivity of the Calton Hill trap. The maximum difference is at a depth of 41 kilometers and amounts to less than 4°. The neglect of the curvature is thus of no consequence.

for an approximate estimate of the relative importance of radioactivity.

The outer part of the earth is essentially a shell of massive rock several hundred miles in thickness. Roche [53] would make this thickness a sixth of the distance to the center, and Wiechert [54] one-fifth. The cooling of the earth must depend almost wholly on the properties of this rock, and the film of detrital matter on the surface bears no greater proportion to the mass of the earth than might the coating of oxide on a hot cannon ball. Hence it seems to me that the value of diffusivity to be chosen is that of trap, and that the significant gradients are those to be found in massive rocks, not among strata. Furthermore, many causes tend to increase the gradient. Such are thermal springs, volcanic heat, dissipation of mechanical energy, chemical decomposition, and radioactivity, while only exceptionally high diffusivity in a massive rock of a given type or the neighborhood of large bodies of cold water tends to lower the gradient. What is requisite for the problem of a cooling earth is not an average gradient, but the average of unexceptional gradients in massive rocks.

Suggestions of this character have been made by various writers, but the subject has been discussed in detail only, so far as I know, by Mr Johann Koenigsberger.[55] He has classified observations on temperature gradient and points out that those taken in nearly level regions in [relatively speaking] chemically unaltered rocks which are not recent eruptives are the most characteristic for the earth as a whole. He gives 26 such values, ranging from 1° centigrade in 27.8 meters to 1° centigrade in 37.9 meters. Five of the 26 are lower than 1° in 37 meters and average 1° in 37.7 meters or, in round numbers, 1° centigrade in 38 meters. This is equivalent to 1° Fahrenheit in 69.3 feet. Since a minimum gradient, rather than an average one, is demanded by the problem, I shall suppose this to be the normal value; and if the gradient due to cooling alone is 1° centigrade to 42.2 meters, as I find it for the 60-million-year earth, the gradient due to radioactivity and other analogous causes would be

$$\frac{1^\circ}{38^m} - \frac{1^\circ}{42^m.2} = \frac{1^\circ}{385^m},$$

or almost exactly a tenth of the normal value.

No doubt this is only a rough approximation. If the earth were only 55 million years old, the other data remaining the same, the remainder attributable to radioactivity would only be 1° in 588 meters, while for a 65-million-year earth it would be 1° in 294 meters.

Again, in spite of Mr Koenigsberger's valuable classification of gradients, we need more information on the normal gradient, as he points out himself—indeed, I understand that he is making observations on the conductivity of rocks and the normal gradient.

Mr A. C. Lane [56] has discussed the gradient in Michigan and considers 1° Fahrenheit

[53] Mémoire Academie de Montpellier, 1882.

[54] Góttingen Nachrichten, 1897, p. 221.

[55] Congrès géologiue Internationale, tenth session, Mexico. Compte Rendu, 1907, p. 1127. In this very important paper Mr Koenigsberger shows that the temperatures in tunnels can be calculated by Fourier's law when the local topography is taken into account.

[56] Annual Report of the Michigan Geological Survey, 1901, p. 244.

in 100 feet an average value in trap and limestone; but the neighborhood of large bodies of water modifies the applicability of this result.

On the whole, however, considering the good agreement between my results for a cooling earth and the age as computed by other means, it seems reasonable to conclude that a tenth represents the order of magnitude of the fraction of the gradient due to such causes as radioactivity, and that it very probably lies between an eighth and a sixteenth.

Geophysicists should not forget, however, that radioactivity is only one of the causes which may influence the gradient. Even relatively fresh rocks are rarely quite undecomposed, and eventually this must be taken into account. The disintegration of a gram of radium liberates millions of times as much heat as the peroxidation of a gram of ferrous silicate; but these silicates are also millions of times as abundant as is uranium.

Mention has been made above of Mr Rutherford's extremely interesting idea of determining the age of uranium minerals from the amount of helium, or preferably of the lead, which they contain, and geologists would assuredly rejoice in the discovery of a valid method of this kind. One condition of its acceptance would clearly be that it should give periods of the same order of magnitude as is indicated by purely geological data.

Now from the helium found in an analysis of fergusonite by Messrs Ramsay and Travers, Mr Rutherford [57] computes an age of at least 500 million years, and from an uranium mineral at Glastonbury, Connecticut, analyzed by Mr Hillebrand, a similar antiquity. The Glastonbury granite gneiss is equivalent to the Wilbraham gneiss of Mr Emerson,[58] who pronounces it unequivocally early Cambrian. Messrs Rice and Gregory [59] feel some uncertainty as to its age, but do not suggest a new position for it. For the present purpose, it is sufficient to regard it as at the bottom of the Cambrian. Mr Walcott's estimate of the lapse of time since the beginning of the Cambrian is nearly 28 million years, or about an eighteenth part of that suggested by Mr Rutherford.

Mr Boltwood [60] has computed the age of a large number of uranium minerals from their lead content. He shows that according to theory the age will be given in years to a first approximation, if the ratio of metallic lead to metallic uranium is multiplied by 10 million. In this way he gets for the age of the Glastonbury minerals 410 million years. Now, at Barringer hill, in Llano county, Texas, there is a very remarkable deposit of rare radioactive minerals, which are so abundant that they have been mined for the use of an electric light company. It happens that the age of the granite in which the pegmatite occurs is known. Mr Walcott [61] discovered in this county his Llano group, which belongs to the Grand Cañon series not far below the Cambrian. The granites are intrusive in these sediments. The great masses of granite which occur in western Burnet and all through Llano county belong to the same age as the strata, and Mr Walcott is careful to remark that he did not observe any rocks of undoubted Archean

[57] Radioactive transformations, p. 189.
[58] U. S. Geological Survey, Monograph 29, 1898.
[59] Connecticut Geological and Natural History Survey, Bulletin 6, 1906, p. 116.
[60] American Journal of Science, vol. 23, 1907, p. 87
[61] American Journal of Science, vol. 28, 1884, p. 431.

age in the region. A number of analyses [62] of the rare minerals of Barringer hill are available, and by Mr Boltwood's rule they give the following ages for the Llano beds:

Yttrialite, J. B. Mackintosh	...	11,470	million	years.
Yttrialite, W. F. Hillebrand	...	5,136	"	"
Mackintoshite, W. F. Hillebrand	...	3,894	"	"
Nivenite, Mackintosh	...	1,671	"	"
Fergusonite, Mackintosh	...	10,350	"	"
Fergusonite, Mackintosh	...	2,967	"	"

Mr Boltwood informs me, however, that, with the possible exception of nivenite, none of these minerals is really suitable for throwing any definite light on the question of the uranium-lead ratio for Llano county, since all of the specimens show signs of incipient or advanced alteration; but, according to theory, the state of combination is without influence on radioactivity, so that the only alterations which would affect the matter must involve the addition or subtraction of uranium or lead, and mere hydration, for example, should be without effect. The nivenite, interpreted by the rule, indicates an age 50 times as great as seems admissible from a geological standpoint and 4 times as great as the Glastonbury mineral, which would seem on geological grounds nearly coeval with it.

There seems to me a plausible explanation of the lack of accord among these minerals. Mr Brögger,[63] from his exhaustive studies of the Norwegian pegmatites, reaches the conclusion that the minerals of the thorite-orangite group, including urano-thorite, crystallize in his first phase of vein formation, that of "magmatic consolidation with the cooperation of pneumatolytic processes." In the second phase, of the "principal phase of pneumatolytic minerals," galena crystallizes out. He has observed galena in so many pegmatites that he considers it superfluous to enumerate them. Now, every one who has had much to do with minerals knows how impure most of them are; how prone to include much more than traces of whatever foreign substances may be present. Brögger's observations show that lead compounds must be soluble in the menstruum from which uraniferous minerals crystallize and indicate the probability that lead may be occluded in them as an impurity, the amount of which may vary from crystal to crystal.

In view of these facts, the proportion of helium in uranium minerals would perhaps afford a better basis than the lead content for estimates of their age. If Sir William Ramsay's determination of the life of radium is correct, Mr Rutherford's helium estimate of the age of fergusonite, referred to above, would reduce to 66 million years, which seems not geologically impossible. But I find no convincing evidence that the law of decay is so simple as is assumed. Under the conditions in which uranium compounds are stable, λ must necessarily reduce to zero. It is in the highest degree improbable that λ is a discontinuous function, and it is to the same degree probable that the law

[62] Hidden & Mackintosh : American Journal of Science, vol. 38, 1889, p. 474.
Hillebrand : American Journal of Science, vol. 46, 1893, p. 99, and vol. 13, 1902, p. 145.

[63] Die Mineralien der Syenitpegmatitgänge, part I, pp. 160, and part II, p. 10.

of decay fails like Boyle's law, or that λ varies with circumstances such as may have environed a mineral in a pegmatite, even though heat alone or pressure alone may be without effect upon radioactivity.

On the whole, then, the surface temperature gradients, taken in connection with the age of the earth as determined stratigraphically, or from the sodium content of the ocean, or from my theory of a cooling earth, do not indicate that the excess of temperature within the earth is due in any large measure to radioactivity. Something like a tenth of the gradient, however, may perhaps be due to this cause—a question which a more discriminating study of gradients will answer, at least in part. It does not seem to me that geologists can possibly accept the ages of minerals as determined from the uranium-helium or the uranium-lead ratios, which do not seem consistent and are far longer than stratigraphers could admit.

5 Distribution of radioactivity in depth

That radioactivity is almost universally distributed over the earth's terrestrial surface has been known for some years; indeed, as Mr Rutherford puts it, each blade of grass must be coated with an invisible deposit of radioactivity material. A forteriori, soil and rocks must possess such a coating and also, so far as they are porous, a radioactive lining.[64] Pioneers in the study of the distribution of radioactivity were the Messrs Elster and Geitel,[65] who have shown that radium is particularly abundant in clays and spring deposits. As has been mentioned, even volcanic matter, especially the porous tuffs, contain some radium, while fresh lavas contain little or none. In 1906 Mr R. J. Strutt made a very valuable series of determinations of the activity of massive rocks, meteorites, and sedimentary strata.[66] This investigation shows that granites and syenites are much more radioactive than other rocks, although some granites—for instance, that from the isle of Rum—contain very little radium. The metallic meteorites show no sensible activity, and stony meteorites only about as much as the basalts—a sixth or an eighth of that shown by the more active granular rocks. Messrs Eve and McIntosh [67] have added a number of American rocks to Mr Strutt's list and have corrected his results by means of an improved ratio between the quantities of uranium and radium existing in substances which are in radioactive equilibrium.[68] The corrected averages for Mr Strutt's igneous and sedimentary rocks are 1.7×10^{-12} and 1.1×10^{-12} or in mean 1.4×10^{-12} grams radium per gram of rock.

[64] See J. Danne on superficial occurences of radium ; Comptes Rendus, Paris, vol. 140, 1905, p. 241, and McCoy and Ross, American Chemical Society, vol. 29, 1907, p. 1702.

[65] Phys. Zeitsch., vol. 3, 1902, p. 574 ; vol. 4, 1902, p. 162 ; vol. 5, 1904, p. 321.

[66] Proceedings of the Royal Society of London, series A, vol. 77, 1906, p. 472, and vol. 78, 1906, p. 150.

[67] Philosophical Magazine, vol. 14, 1907, p. 23.

[68] Rutherford and Boltwood found that the amount of radium associated with 1 gram of uranium during radioactive equilibrium is approximately 3.8×10^{-7} gram. American Journal of Science, vol. 172, 1906, p. 1. See also A. S. Eve, ibid., p. 4. Mr Strutt's paper was read before the appearance of this corrected ratio.

It is evident that the radioactivity of rocks must tend to raise their temperature and to increase any temperature gradient which they might have were radium absent. This was first pointed out in 1893 by Mr F. Himstedt.[69] In the next year Mr Rutherford [70] showed that the amount of heat indicated by Messers Elster and Geitels' determinations of the radioactivity of soils far exceeded the average amount lost by the earth through radiation. In the same year Mr C. Liebenow [71] reached the same result independently and inferred that radium, or at least the disintegration of radium, must be confined to small depths, since otherwise the earth would be growing hotter. Within this shell the temperature would be constant if all the heat were due to radioactivity.

Early in 1906 the distribution of temperature in a globe heated exclusively by radium was discussed almost simultaneously by Mr J. Koenigsberger [72] and Mr R. J. Strutt.[73]

Mr Koenigsberger, starting from Fourier's equation for the conduction of heat in three dimensions, discusses several distributions of radium: (1) a uniform distribution throughout the globe, (2) a uniformly active shell, (3) a sphere in which the activity fades out gradually in depth, and (4) an active shell buried beneath an inactive layer of rock.[74]

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[69] Verhand. Freiburg. nat. Ges., vol. 14, 1903, p. 186, and Phys. Zeitsch., vol. 5, 1904, p. 210.

[70] Radioactivity, 1904, p. 344.

[71] Phys. Zeitsch., vol. 5, 1904, p. 625.

[72] Phys. Zeitsch., vol. 7, 1906, p. 297.

[73] Proceedings of the Royal Society of London, series A, vol. 77, 1906, p. 472.

[74] The partial differential equation representing the conduction of heat in a sphere is by Riemann's Partielle Differentialgleichungen, section 61:

$$\frac{d(ur)}{dt} = \frac{k}{c}\frac{d^2(ur)}{dr^2},$$

where u is the excess of temperature, as compared with the surface, of a point at a distance r from the center; k is the conductivity; c the thermal capacity, and t the time. If q is the quantity of heat liberated per second per cubic centimeter by radioactivity, the rate at which the temperature would rise is q/c. If the earth is in thermal equilibrium, the heat lost by conduction per unit of time must be equal and opposite to q/c. Hence

$$\frac{du}{dt} = -\frac{q}{c};$$

and since r does not vary with t,

$$r\frac{du}{dt} = \frac{d(ur)}{dt} = -\frac{qr}{c}.$$

Consequently

$$\frac{d^2(ur)}{dr^2} = -\frac{qr}{c}$$

represents the distribution of temperature in any radioactive sphere in which the radium is symmetrically distributed with reference to the center.

When q and k are constant for such a portion of the sphere as is radioactive, the integral of this expression contains two arbitrary constants. If the problem to be discussed is that of a superficial shell of radioactive matter, let R be the outer radius of the earth and R_0 the inner radius of the shell. Then du/dr must vanish, for $r = R_0$ and u must be zero at the surface or when $r = R$. The complete solution is then

$$\frac{ku}{q} = \frac{R^2 - r^2}{6} - \frac{R_0^3}{3}\left(\frac{\ell}{r} - \frac{\ell}{R}\right); \frac{du}{dr} = -\frac{q}{3k}\left(r - \frac{R_0^3}{r^2}\right)$$

Mr Strutt independently reached the equation of the distribution of temperature in a thin radioactive shell uniformly charged with radium.[75] He computed the thickness of the crust at 45 miles and the temperature of the interior at 1530° centigrade, assuming a surface temperature gradient of 1° Fahrenheit in 42.4 feet. His constants have been in part superseded, and I have therefore recomputed his equations for a gradient of 1° Fahrenheit in 50 feet with the conductivity of the Calton Hill trap, 0.00415, assuming that the thermal effect of 1 gram of pure radium is 100 gram calories per hour. It follows that the thickness of the radioactive shell needful to maintain the temperature gradient is 137 kilograms if it contains 1.4×10^{-12} grams of radium per gram of rock uniformly distributed, while the resulting internal temperature would be no less than 2488° centigrade, which seems high.

As is well known, Mr Barus investigated the melting point of diabase, finding that it rose in simple proportion to the pressure. At a depth of 137 kilometers diabase would melt at about 2100° centigrade; hence a temperature of 2488° at this depth would imply a liquid couche and consequently tidal instability, which is inadmissible.

Evidently, then, there must be a limit to the effects which can be attributed to radioactivity, and with the data in hand a surface gradient of 1° Fahrenheit in 50 feet can not be accounted for in this manner. The limitations are easily determined from Mr Strutt's equations, which may be written

$$v = \frac{qx}{2k}(2s - x); \frac{dv}{dx} = \frac{q}{k}(s - x)$$

where v is the temperature excess; q the quantity of heat developed in the radioactive shell per cubic centimeter per second; k the thermal conductivity of the rock; s the thickness of the shell, and x the distance from the surface. The temperature at which diabase melts may be represented with sufficient accuracy by

$$y = 1170° + 67.5 \times 10^{-6}x.$$

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for a sphere which is radioactive throughout $R_\circ = o$ in these formulas. If, on the other hand, the shell is thin, let $R - r = x$, where x is the distance from the surface, and let $R - R_0 = s$ the thickness of the shell. Then x/R will be a small quantity and the formulas reduce to the form employed by Mr Strutt and which will be used here in the text. As Mr Koenigsberger shows, q may, if desired, be regarded as a function of r; for example, q' may be constant, such that

$$q'r^n = q;$$

so that the radioactivity vanishes at the center of the earth and is greatest at the surface. The differential equation may still be integrated with ease. Again, k may be supposed to vary with the temperature. I may observe, however, that it can not really vary by such a law as $k = k_0(\ell - \alpha u)$, for then when $u = \ell/\alpha$, $k = 0$, and this would mean that a body heated to a temperature ℓ/α would never cool at all!

In a sphere of initially uniform temperature cooling according to Fourier's law, the temperature gradient is a maximum at the surface and decreases continuously with increasing depth. By an inadvertence, Mr Koenigsberger states that in this case the gradient increases with depth.

[75] When the curvature of the earth is neglected, this problem is mathematically identical with that of the heating effect of a constant electric current on a thermally insulated conducting wire. Cf. Kohlrausch, Lehrbuch der prak. Physik, 10th edition, p. 214.

If the v curve is tangent to this diabase line at x_0, it is easy to eliminate s and show that

$$x_0 = \sqrt{2.\frac{1170k}{q}}$$

Then with the conductivity of the Calton Hill rock, 0.00415, the density 2.85, and the heating effect of radium 0.02778 gram calories per gram per second,

$$q = 1.4 \times 10^{-12} \times 2.85 \times 0.02778 = 0.1108 \times 10^{-12}; x_0 = 93.6 \text{ kilom.}$$

The condition of tangency gives

$$\frac{q}{k}(s - x_0) = 67.5 \times 10^{-6}$$

or

$$s = 119. \text{ kilometers } = 74 \text{ miles.}$$

and when $x = s$ or for the under surface of the shell

$$v = \frac{qs^2}{2k} = 1887^\circ \text{ centigrade.}$$

Finally, when $x = o$, the surface gradient is

$$\left(\frac{dv}{dx}\right)_\circ = \frac{qs}{k} = 0.0003176^\circ \text{ centigrade per centimeter,}$$

or 1° Fahrenheit per 57.4 feet.

I am thus led to the striking conclusion that with the data now known any surface gradient of temperature due to uniform radioactivity alone, which exceeds 1° Fahrenheit in 57 feet, would result in tidal instability and is impossible. The utmost thickness which can be ascribed to a shell of uniformly radioactive rock is 74 miles and the highest temperature which its under surface can possess is 1887° centigrade.

The surface gradient, 1° Fahrenheit in 57 feet, or 0.03176° centigrade per meter, or 1° centigrade in 31.5 meters, is well within the range of observed gradients; but if all the heat of the earth is to be accounted for by radioativity, it appears too low. Mr Strutt, following Prestwich, took 1° Fahrenheit in 42.4 feet as the mean, and Mr Rutherford 1° Fahrenheit in 50 feet.

As appears from the formulas, the surface gradient is simply proportional to the thickness of the shell or to s. Hence, if only a fraction of the actualy gradient is due to radioactivity, the corresponding thickness of the radioactive shell can be found by simple proportion. Thus if the normal average gradient is 1° centigrade in 38 meters and the average gradient due to radioactivity is 1° in 385 meters, the values suggested on a preceding page for a 60-million-year earth, then the radioactive shell would be 9.8 kilometers, or about 6 miles, in thickness. The corresponding thickness for ages of 55 and 65 million years are respectively, in round numbers, 6 kilometers and 13 or 4 miles and 8.

While there are limitations to the possible thickness of a uniformly radioactive layer, there are also reasons for believing that radioactivity is not uniformly distributed, and that it is at a maximum not more than a few thousand feet from the solid surface of the earth.

In this connection the radioactivity of the ocean presents points of great interest. Mr Strutt [76] and Mr A. S. Eve [77] have made determinations of the activity of sea salt and Mr J. Joly [78] of abysmal sediments. Mr Eve finds that sea water does not contain per gram more than 6×10^{-16} grams radium, or only a three-thousandth part as much as Mr Strutt's igneous rocks, and he infers that the uranium denuded from the land is deposited in oceanic sediments. Mr Joly obtained from Sir John Murray globigerina ooze from a depth of 1,990 fathoms and red clay from 2,740 fathoms. The former contained 6 times as much radium as Mr Strutt's igneous rocks and the latter 16 times as much.

The activity of the ocean itself is almost negligible. Its average depth is about 3,440 meters (Woodward) and its density 1.027 (Clarke), so that the weight per square centimeter is 353,300 grams. Dividing by 3,000 gives the weight of Mr Strutt's rock, which would be radioactively equivalent, and dividing again by 16 gives the corresponding weight of Mr Joly's clay. If the density of this clay is supposed to be 2.75, it follows that the whole ocean has a radioactivity no greater than that of a layer of clay 27 millimeters, or a trifle over one inch in thickness!

If radium emanation were a permanent gas, ocean water would be charged with it, according to Henry's law; but the half-value period of radium emanation is only 4 days and its average life therefore 5.8 days. In so short a time as six days this heavy gas, liberated at or beneath the ocean bottom, would diffuse vertically through the water to a short distance only, and, since its non-volatile products appear substantially insoluble in sea water, they would subside again to the bottom. In this way it would seem that a concentration of radium D and subsequent members of the series, including lead, must take place. As a matter of fact, an extremely careful analysis [79] has been made in the laboratory of the U. S. Geological Survey of a composite sample of red clay prepared by Sir John Murray from 35 specimens, and it showed 80×10^{-6} grams lead oxide per gram of clay. If any considerable part of this lead resulted from the disintegration of uranium, it is substantially certain that concentration has taken place; for the equivalent amount of radium is over $3^1/_2$ million times the quantity found by Mr Joly in the clay. The data, however, are too few to justify more than the qualitative conclusion that an intelligible tendency is indicated to the concentration of radioactive matter on the sea bottom. On the other hand the depth of the red clay is entirely unknown, and for that reason it seems to me impossible to judge for how long a period radioactive matter has been accumulating in the ocean.

If a continuous sheet of water is practically impermeable by radium emanation,

[76] Proceedings of the Royal Society of London, series A, vol. 78, 1906, p. 150.
[77] Philosophical Magazine, vol. 13, 1907, p. 248.
[78] Nature, vol. 76, 1907, p. 8.
[79] F. W. Clarke : Proceedings of the Royal Society of Edinburgh, vol. 27, part iii, 1907, p. 167.

lakes and ground water likewise greatly interfere with the escape of this gas; and on land also, so far as ground water exists, there must be a tendency to the concentration of radioactive substances. Recent studies show that underground waters are more superficial than was formerly supposed, and that meteoric waters are not abundant below a depth of a couple of thousand feet, exepting along certain fissures. The vadose circulation in most cases with extreme slowness and its waters must interpose a formidable obstruction to the diffusion of radium emanation, or must greatly promote its disintegration within the capillary fissures of rock-masses; hence also it seems to me that there must be a concentration of radioactive matter in water-bearing rocks. If so, rocks from desert areas not associated with pegmatite should show on the whole less activity than similar rocks from moist regions; so also rocks collected in very deep mines dry at the bottom should be less active than those of the overlying wet layer, and in general radioactivity should be at a maximum in the outer moist shell of the earth. This is in line with what is known of the radioactivity of volcanic rocks, and the interference is one which ought to be tested by exploration.

Radioactive clays at the ocean bottom doubtless evolve heat in the same proportion as they would at sealevel, but the temperature effects must be inconsiderable, because the clays are soaked with very cold water. Convection currents will be stimulated to some extent by the heat evolved, and this will be the principal effect. In continental regions also the vadose circulation is equivalent to a water jacket, and radioactive heat will be carried off by the slowly moving water currents. This fact is another reason for believing that the best field for the study of the effects of radioactivity on the earth as a whole is an arid one, such as the Great basin. If the congressional appropriation for chemical and physical research were not so very small, I should endeavor to have a radioactive survey made of the region of the Grand canyon of the Colorado; but that must wait.

It appears that uranium and its disintegration products originate in the granitic rocks; that radium must be confined to a relatively thin shell; that no gradient higher than 1° Fahrenheit in 57 feet can be accounted for by uniform radioactivity, and that average radioactivity is probably a maximum where water interferes with the escape of radium emanation. It also appears inevitable to ascribe a great part of the temperature gradient of the earth to its original heat. The whole subject would be much clearer if the origin of granite and the depth to which it extends were known.

That the granites are relatively superficial seems to be proved by their low density, the relatively small silica of most modern effusive rocks, which must come to the surface through granite, and finally the absence of tridymite, together with the presence of much water in the granular rocks.

If, as Kelvin believed and as it seems rational to believe, the rocks of the earth's lithoid shell consolidated at their melting temperatures, no granitic rocks can have formed until all the others had congealed. It does not seem possible consistently to imagine a globe in the process of cooling in which a layer of freshly consolidated basalt surface would have a temperature of 1170° plus an amount corresponding to the pressure at that particular depth, while since the inversion point of tridymite at atmospheric

pressure is some 800°, the lower surface of granitic sea would have a temperature of, say, 800° plus an amount corresponding to the pressure. A temperature gap or discontinuity would exist between the two rocks. Under such conditions, if they could exist, the lower part of the granite would rapidly pass over into rhyolitic or trachytic magmas and the temperature curve would be inflected. On the other hand, I find no difficulty in imagining the earth consolidating to a surface of rhyolitic or trachytic composition similar perhaps to that which the moon now presents to our vision, but at a temperature of, say, 1300°. The surface would be white hot and the atmosphere would contain, *inter alia*, almost all of the water of the globe at a temperature nearly a thousand degrees above its critical temperature. Surely when the sun solidifies there will be such an epoch in its history, and the small density of Jupiter points to the existence of such conditions there. As soon as the surface of the earth solidified, its temperature must have sunk with great rapidity to the critical point of water (365°), and at the enormous atmospheric pressure of several hundred kilograms per square centimeter the intensely heated aqueous vapors must have acted on the rhyolitic shell with extraordinary energy. They were not forced in under pressure, but sucked in by the shrinkage of the cooling lava. Here, then, were ideal conditions for aqueo-igneous fusion and for the formation of granitic rocks from rhyolitic and trachytic massives.

Thus the formation of primitive granitic rocks may rationally be coneived as due to a refusion immediately following the consistentior status and extending as far from the surface as aqueous vapors could penetrate. How far that would be it is, to be sure, as yet impossible to say—a mile or two at least, it may be guessed, but probably not many miles.

The thermal relations of the formation of primeval granite, as sketched above, are complex. Aqueous vapor was condensed and united with the rhyolitic material to a magma of a lower temperature than the rock had possessed before aqueo-igneous fusion. Heat was liberated by the condensation of the vapor and the cooling of the magma, but heat was absorbed by the liquifaction of the rock. Now the absorption of heat in the dry fusion of orthoclase is small, and I know of no indication that it would be great in the aqueo-igneous fusion of granite, while the heat liberated by the condensation of aqueous vapor is, of course, enormous. Though no exact balance can be struck, it would seem as if the primeval granite must have formed very slowly indeed, unless by some means surplus energy could be potentialized. In the absence of such a disposition of the excess, granite could form only as fast as radiation from the surface reduced the temperature at internal levels to the point at which silica crystallizes as quartz. On the other hand, if energy could be potentialized within the mass, the tendency to stable thermal equilibrium would be fulfilled with comparative rapidity, and such tendencies usually involve adjustment at a maximum rate.

The bounds of legitimate hypothesis are not transgressed by supposing that the surplus energy of aqueo-igneous refusion was potentialized by the formation of uranium, and that the energy of radioactive matter thus represents a part of the original energy of the cooling globe. If so, the solidification of the primeval granite was hastened by the genesis of uranium, and the head which now escapes from its disintegration

products would have been radiated into space long since if no such complex atoms had been stable under the conditions of aqueo-igneous fusion. The earth has cooled more gradually because of an endothermic reaction, but the source of its heat is dynamic.

Although there is reason to believe that the radium content of the rocks is at a maximum in or just below the vadose waters, this does not affect the computation of the total amount of radium from the difference between the normal gradient and the gradient for a given age. This follows from the assumption that all the head generated by the disintegration of radium is emitted from the surface and in so far its distribution is unimportant. If, however, the amount of radioactivity diminishes with depth, the shell of radioactive matter must be thicker than that computed.[80]

Although the contribution of radioactivity to the total heat of the globe appears to be relatively small, the influence of radioactivity on geological processes may have been great. So far as the action of "mineralizers" is understood, it would seem that radioactive matter should be extraordinarily efficient. It is hard to see how any chemical or physical reaction would hang fire under the bombardment of α particles, which seems comparable to the explosion of fulminate mercury. The influence of radium on crystallization of artificial minerals ought to be studied, and it will be strange if it is not found useful. Mining geologists and petrographers also should endeavor to ascertain whether phenomena hitherto mysterious are not explicable by radioactivity, but they will probably meet with little success until further systematic laboratory researches have been made with the especial purpose of elucidating the subject. Unfortunately there seems no hope of this until the fundamental importance of geophysical researches is more generally appreciated.

6 Summary

This paper begins by an attempt to outline in sufficient detail for the use of geologists the magnificent investigations of a small group of physicists on radioactivity. While a few matters are still in doubt, these are relatively unimportant to geologists, and it is

[80] If the heat developed by radioactivity were greatest at the surface, say equal to q_0, and diminished linearly with depth, vanishing when the depth were σ, then the heat developed per cubic centimeter would be

$$q = q_0\left(1 - \frac{x}{\sigma}\right) \text{ and } \frac{d^2v}{dx^2} = -\frac{q_0}{k}\left(1 - \frac{x}{\sigma}\right)$$

Making the temperature gradient zero when $x = \sigma$ and the temperature excess, of v, zero at the surface, the equations

$$\frac{dv}{dx} = \frac{q_0\sigma}{2k}\left(1 - \frac{2x}{\sigma} + \frac{x^2}{\sigma^2}\right);\ v = \frac{q_0\sigma}{2k} \cdot x\left(1 - \frac{x}{\sigma} + \frac{x^2}{3\sigma^2}\right)$$

represent the distribution of gradient and temperature. The surface gradient in this case is

$$\left(\frac{dv}{dx}\right)_0 = \frac{q_0\sigma}{2k}$$

and the curvature of the temperature curve is considerably nearer the surface, because in this neighborhood d^2v/dx^2 is finite. On the other hand, at the bottom of the radioactive layer d^2v/dx^2 vanishes. In the case of a cooling globe the curvature of the excess temperature is zero at the surface.

fully established that radioactivity must be taken into account in estimating the age of the earth as well as in the explanation of geophysical phenomena.

The second section deals with the origin of the radioactive elements. The distribution of elements in the universe as revealed by the spectroscope is discussed in connection with Mr Clarke's evolutionary hypothesis. The distribution, taken in its relations to the periodic law, points to the truth of the hypothesis that elements are evolved, those of the highest molecular weight being the youngest and confined to cooling stars or planetary bodies. This conclusion is in line with Mr J. J. Thomson's corpuscular theory of matter and evolution is the converse of the devolution established by the Curies and Messrs Rutherford and Soddy. If uranium existed in the nebulæ the mystery of the universe would be almost hopelessly deepened. Regarding uranium as an endothermic compound, it must be stable at certain elevated temperatures and pressures. Its association with pegmatites indicates in a general way the conditions of stability, and it is pointed out that the artificial production of radioactive substances is not a hopeless aspiration.

The bearing of radioactivity on the age of the earth is next considered. The more important estimates—geological, chemical, astronomical, and physical—are assembled, including a new calculation of the age of a cooling globe made for this memoir, but published in detail elsewhere. This agrees with the determination by other methods and gives about 60 million years as the age. From it may be deduced a gradient of 1° centigrade in 42.2 meters, while the best normal value of the gradient as derived from Mr Koenigsberger's discussion is 1° centigrade in 38 meters. The difference, about one tenth of the latter, is offered as a first approximation to the terrestrial heating effect of radioactive substances. The theory that the age of minerals can be inferred from the ratio of uranium to helium or to lead is discussed and rejected.

A concluding section is devoted to the distribution of radioactivity in depth. The total heating effect is independent of this distribution, which, however, would affect the rate of increase of temperature in mines or wells, and something may possibly be learned of it by such means. Formulas for the temperatures due to various distributions have been given by Mr Koenigsberger and Mr Strutt. It is shown how that for a uniformly radioactive shell the highest surface gradient compatible with tidal stability is 1° Fahrenheit to 57 feet, while if the gradient due to radioactivity is a tenth of that due to cooling, the uniformly radioactive shell is a little less than 10 kilometers in thickness or, say, between 6 and 13 kilometers. The ocean has scarcely any radioactivity, while the abysmal red clay is intensely active. A plausible hypothesis is offered for the accumulation of radioactive matter beneath water or wet rocks. The intimate association of radium and granitic rocks leads to the consideration of the conditions of the formation of primeval granite. The only origin compatible with known facts seems to be the action of superheated aqueous vapor on solid nearly anhydrous rhyolitic or trachytic rocks, producing aqueo-igneous fusion immediately after the consistentior status. This would apparently imply that the granitic shell is not more than a few miles in thickness and is consistent with the inference as to the thickness of the radioactive shell. The thermal relations seem to indicate that the formulation of granite must

have been excessively slow, unless by some means energy was potentialized. Now the formation of uranium potentialized an enormous amount of energy. Hence it is reasonable to believe that the formation of uranium took place at this time and at the expense of the heat of compression of the terrestrial nebula.

Notes About This Edition

Which Parts Are Most Important

This is kind of a long document, and not all of it is necessary for a person studying the history of geology. The two most important sections to read are Section 4 *Radioactivity and the earth's age* and Section 6, the summary. These are the sections which help to disprove the reliability of radiometric "dating." The way Becker went about disproving radiometric "dating" is to compare it against other dating methods which were trusted by geologists. Specifically, Becker points out that Kelvin's temperature gradient argument, Joly's oceanic sodium argument, as well as arguments from stratigraphy all seemed to put the solidification of the earth's crust at about 100 million years ago or less, but definitely not more. This is contrasted with radiometric "dating," which has a tendency to produce numbers laughably in excess of these limits[81]. It's historically important that it was known *already in 1908* that radiometric "dating" couldn't be trusted to any degree—and yet here we are.

Section 5 *Distribution of radioactivity in depth* is also an important section to read, since in this section Becker argues that the thermal energy contained in the earth can't be due in a large part to radioactivity. The people who desparately wanted to believe in billions of years had to rely on the *assumption* that the majority of the thermal energy would be due to radioactivity. Becker points out though that the radioactivity of the earth would be necessarily limited to a small outer shell of radioactive material; for if the earth had radioactivity all the way through, this would make it so that the earth would still be heating up even today, or even introduce a tidal instability. The end of Section 5 will sound a little bit more speculative, since Becker hypothesizes about the formation of radioactive substances within the earth.

Section 2: *Outline of radioactivity* can be skipped by a person who already understands basic nuclear chemistry, although a person interested in the history of the subject might still enjoy reading it.

Section 3 *Origin of uranium and thorium* can be skipped. For those interested in the history of science, it contains a more primitive version of the periodic table of elements, but other than that it's mostly a dry overview of the distribution of various elements in light from various astronomical sources. It also contains speculations about the origins of uranium and thorium. Nowadays it's generally assumed that heavy elements are assembled at different parts in the life-cycle of stars. Neither the speculations mentioned by Becker more than a century ago, nor our modern speculations, have ever been tested, so these are really just stories we tell ourselves.

So at least read Section 5, Section 6, and the Summary at the end.

[81] Radiometric "dating," it should be mentioned, can also just be rejected on the grounds of basic logic and mathematics, since unjustifiable assumptions have to enter into the analysis in order for any numbers to be calculated. In reality, Becker's comparison against these other techniques was unnecessary, but he also alluded to this logical problem when he mentioned the work of Brögger. The logical problem is not the purpose of this document though.

Dated Terminology

Here I spell out some of the terminology that was employed in this paper, since some of it will be unfamiliar to modern readers.

For the reader's reference, nebulium was believed to be an element at the time Becker's paper was written, but it was only ever known from spectral analysis of astronomical objects. It was later discovered that its spectrum matched that of doubly ionized oxygen, so nebulium isn't actually an element but a state of oxygen.

Coronium, which is also mentioned in this paper, was later similarly determined to be a highly ionized state of iron. Therefore neither nebulium nor coronium were genuine elements, but ions of already known elements.

Then there's radon: Nowadays "radium emanation" is abbreviated as "radon." The other emanations, namely "thorium emanation" and "actinium emanation," were later found to be isotopes of radon, and so today they're all simply called "radon" (even though there *was* a time when they were called "thoron" and "actinon" respectively, and these are still accepted names for the different isotopes).

Typos and Motivation

Anyway, Becker's words have been preserved to the best of my ability. A few of his typos have been corrected though. At one point, he used the term "nebelium" when he obviously meant to write "nebulium." Another typo that was fixed was when Becker wrote "centrigrade" but obviously meant to write "centigrade." Moreover, there was a point where Becker cited a measurement by F. W. Clarke, and he intended to cite him by saying "(Clarke)" but that he obviously forgot to put the opening parenthasis, only writing "Clarke)," so I restored it.

The reason I've decided to re-typeset this paper is because it's one of the most important papers in early twentieth century geology. This paper showed that as early as 1908, just a few years after Rutherford first conceived of radiometric dating, there was *already* very good reason not to believe it. And yet despite this paper's importance, it isn't easy to find online. I really had to go digging for this paper, but I was able to find it in the middle of a very long document that was uploaded to the Internet Archive by the Smithsonian. (It looks like the document on the Internet Archive that I linked to is also mislabeled as being from 1890, not 1908.)

—Joko