k7 Pioneer radioactive dating methods < helium, U and Th to Pb >

> The helium observed in the radioactive minerals is almost certainly due to its production from the radium and other radioactive substances contained therein. If the rate of production of helium from known weights of the different radio-elements were experimentally known, it should then be possible to determine the interval required for the production of the amount of helium observed in radioactive minerals, or, in other words, to determine the age of the mineral. This deduction is based on the assumption that some of the denser and more compact of the radioactive minerals are able to retain indefinitely a large proportion of the helium imprisoned in their mass.—Rutherford, 1906.[1]

Among the elements present when igneous rocks crystallize will be uranium, thorium, and lead. In acidic igneous rocks there is a natural separation of lead from uranium and thorium. The ionic radius of lead (1.31 Å) allows it becomes fixed in the place of potassium (1.33 Å) in the open lattices of the minerals potassium feldspar and micas as these crystallize. By contrast, the smaller ionic radius of uranium (1.0 Å) and thorium (1.1 Å) keeps them from settling into the growing crystal lattices of those minerals. However, they are incorporated into the denser accessory minerals: zircon, $Zr[SiO_4]$; sphene, $CaTi[OSiO_4]$; and, apatite, $Ca_5[F(PO_4)_3]$. These accessory minerals, because their total volume is small, are often strongly radioactive therefore. Zircon crystals enclosed in biotite mica in acidic igneous rocks, have long been known to be surrounded commonly by a bleached zone called a *pleochroic halo* (***Figure k7.1***). An explanation for pleochroic halos could be given after radioactive processes had become known. Alpha particles, which exit the nuclei of radioactive element like bullets, damage the structure of the mica to the average distance that they travel before being brought to a stop by collisions with its atoms. Uranium, an alpha particle (helium nucleus, 2p2n) emitter, was found by chemical analysis to be commonly present in zircon as a trace element.

In 1902, Ernest Rutherford and Frederick Soddy had found that radioactive elements *fissioned* (term was coined in 1939 by Otto Frisch nephew of Lise Meitner when she reasoned out the process with him)[1] into other elements in a definite sequence or series. The possibility of using radioactivity to measure geologic time was first alluded to by Rutherford in 1904. In 1906, using Ramsey's analysis of helium and uranium in fergussonite, Rutherford calculate a rough age for it of 500 million years.[2]

Bertram Borden Boltwood (1870-1927) noted in passing that "Mme. Curie is just what I have always thought she was, a plain darn fool" [3] (an opinion different from that of her second daughter Eve)[4] and importantly that in uranium and thorium containing minerals (aeschynite, allanite, carnotite, euxenite, fergusonite, gummite, mackintoshite, monazite, orangite, samarskite, thorianite, thorite, uraninite, uranophane, xenotime) lead is always present. Using analyses of 43 uranium minerals from all parts of the world he found that when these were ranked by their stratigraphic age, the amount of lead to uranium present is relatively greater in the older. He inferred (from this *stamp collecting*, please note) that the "radioactive series" leading from uranium ended with lead, which is nonradioactive. (Definitive tests of the truth of his inference followed after Francis W. Aston's invention in 1919 of a mass spectrometer that, with design improvements, can resolve isotopes.[5] Isotope analyses show, for example, that radiogenic lead, and no significant amount of common lead, is present in zircons that contain uranium.)[6] Boltwood realized that the ratio of lead to uranium in a mineral also gave him a radiometric clock, the time keeping of which could be known by the use of analytical techniques available to him. These techniques included atomic adsorption spectrophotometry (not very accurate by later standards) to measure the amount of trace elements in a sample, and a Geiger counter. The latter allowed him to estimate how many atoms of uranium were decaying per unit time by the number of alpha particles being emitted per unit time. The rate at which the uranium decays is a constant. A rough and ready hypothesis is

that the age of a mineral can be known by the ratio of lead to uranium in it divided by the rate of uranium decay (***Footnote k7.1***). The rate he determined was that one ten-billionth of uranium atoms change to lead atoms in the time of a year. In 1907, he published the ages for ten mineral occurrences. Their ages were startling in every case: the youngest was for a uraninite (uranium oxide) from Glastonbury, Connecticut, with a lead/uranium ratio of 0.041 (average of five analyses) and hence an estimated age of 410 million years (a hundred million years on the high side by latest estimates), and the oldest was a thorianite (thorium and uranium oxide) from Ceylon with a lead/uranium ratio of 0.22 and hence an age of 2,200 million years (considerably on the high side because Boltwood treated thorium as a stable element that did not yield radiogenic lead).[7]

Rutherford (radiophysicist) and Boltwood (radiochemist) had given back the geological time that Kelvin (physicist) would have taken away. ❑

Footnote k7.1 The approximate radioactive decay formula

The course of radioactive decay described by **Ernest Rutherford** (1871-1937) in 1900 is easy to graph (*see Figure k5.1*). In 1910, Harry Bateman (1882-1946) pointed out that the same is expressed by the equation [8]

$$t = \frac{1}{\lambda} \ln\left(1 + \frac{D_t}{N_t}\right)$$

In practice N_t can be very much greater than D_t. When this is so

$$\ln\left(1 + \frac{D_t}{N_t}\right) \sim \frac{D_t}{N_t}$$

and for such cases it is reasonable to write

$$t = \frac{1}{\lambda} \frac{D_t}{N_t}$$

Boltwood used this approximate radioactive decay formula (but without mathematical justification) in his pioneer work in radiometric dating.[9] So also did Arthur Holmes in his pioneer use of the results of radiometric dating to transform the geologic column into a geologic time scale [10] (even when it was understood that the approximation is best limited to determining ages that are *less* than one half-life).[11] Also, his influential textbook *Principles of Physical Geology*, though its many editions beginning in 1946, recommended to fledgling geologists the image that a radioactive mineral keeps "a material register of time, after the manner [*sic*] of an hour-glass." [12] The actual flow of dropping sand in an hourglass defies visual measurement. What is measured is the time to when, in a turned hourglass, the flow stops. And misleading is the image of a lit candle or a joss stick designed to burn down at a constant rate. The approximate radioactive decay formula in the place of the full one made available by Bateman (above), has application limited to radiometric dating *only* when the half-life greatly exceeds the age of the material that is dated. Assumed uncritically, and when generalized for application in other contexts, an hourglass analogy and the burning candle or joss-stick analogy of that analogy (!) is counter intuitive as modeled is the constant delivery of some quantity in a way that is unaffected by a dwindling amount in the source and any arbitrary change to more or less of that amount. No geological phenomenon or process can be described that accords to such a scenario.

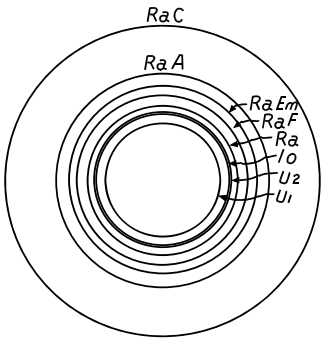

Figure k7.1 [13] **Pleochroic halo**: a set of discrete, concentric rings in biotite mica. The rings show pleochroism (vary in color with different directions of transmitted polarized light) and encircle uraniferous inclusions (often zircon). They are produced by the emission of alpha particles from various isotopes of the uranium and thorium decay series. The energy with which an alpha-particles is discharged is recorded by a definite ring radius and the same can be related to the decay rate of the emitting isotope. The rings of even very old pleochroic halos (that have not been bleached) show no blurring. By implication, there has been no change in decay rates during measured geologic time. This corroborates the principle of actualism.