Chapter 3

Radiohalos in Granites: Evidence for Accelerated Nuclear Decay

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Abstract. The ubiquitous presence of ^{238}U and ^{210}Po, ^{214}Po, and ^{218}Po radiohalos in the same biotite flakes within granitic plutons formed during the Flood falsifies the hypothesis that all granites and Po radiohalos were created, but testifies to the simultaneous formation of these radiohalos. Thus if the Po radiohalos were formed in just a few days while the fully-formed ^{238}U radiohalos were simultaneously generated by at least 100 million years worth (at today's rates) of radioactive decay, radioisotope decay had to have been accelerated. Therefore, conventional radioisotope dating of rocks based on assuming constancy of decay rates is grossly in error. Accelerated radioisotope decay of ^{238}U in zircons within the biotites rapidly formed the ^{238}U radiohalos and produced large quantities of the short-lived ^{222}Rn and Po isotopes. Hydrothermal fluids released by the cooling granitic magmas then transported those isotopes along the biotites' cleavage planes to deposit the Po isotopes in chemically conducive, adjacent lattice defect sites, on average only 1 mm or less distant. The hydrothermal fluids progressively replenished the supply of Po isotopes to the deposition sites as the Po isotopes decayed to form the Po radiohalos. Because of the annealing of α-tracks above 150°C, all the radiohalos only formed below 150°C. However, the U-decay and hydrothermal fluid transport started while the granitic rocks were crystallizing at higher temperatures. Therefore, the granitic magmas must have cooled rapidly or else the short-lived Po isotopes would have decayed before radiohalos could have formed. It is thus estimated that granitic plutons must have cooled within 6–10 days, and that the various Po radiohalos formed within hours to just a few days. The heat generated

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by accelerated radioisotope decay and tectonic processes during the Flood would have annealed all radiohalos in Precambrian (pre-Flood) granitic rocks at that time, so the few radiohalos now observed in these granitic rocks had to have formed subsequently by secondary hydrothermal fluid transport of ^{222}Rn and Po isotopes in their biotites during the Flood. While convective flows of hydrothermal fluids moved and dissipated heat from granitic plutons in days, that mechanism alone would not seem capable of removing the enormous quantities of heat generated by accelerated radioisotope decay over that brief timescale. Other mechanisms must have operated to allow for the survival of the biotites and their ^{238}U and Po radiohalos. The discovery of plentiful Po radiohalos in metamorphic rocks extends the application of the hydrothermal fluid transport model for Po radiohalo formation to these rocks. This confirms that hydrothermal fluids transformed deeply-buried sedimentary rocks to regional metamorphic complexes, which then had to have cooled within days for the Po radiohalos to have formed. Additionally, the prolific Po radiohalos found in granitic and metamorphic rocks and veins that host metallic ore lodes reflect the passage of the hydrothermal fluids that transported and deposited the metallic ores. This suggests such hydrothermal ore veins formed rapidly, and that Po radiohalos could provide an exploration tool for locating new ore lodes. Thus Po radiohalos provide powerful evidence of many rapid geological processes consistent with both the year-long catastrophic global Biblical Flood, and a young earth.

1. Introduction

Radiohalos (abbreviated from radioactive halos) are minute circular zones of darkening surrounding tiny central mineral inclusions or crystals within some minerals. They are best observed in certain minerals in thin microscope sections of rocks, notably in the black mica, biotite, where the tiny inclusions (or radiocenters) are usually zircon crystals. The significance of radiohalos is due to them being a physical, integral historical record of the decay of radioisotopes in the radiocenters over a period of time. First reported between 1880 and 1890, their origin was a mystery until the discovery of radioactivity. Then in 1907 *Joly* [1907] and *Mügge* [1907] independently suggested that the darkening of the minerals around the central inclusions is due to the alpha (α) particles produced by α-decays in the radiocenters. These α-particles damage the crystal structure of the surrounding minerals, producing concentric shells of darkening or discoloration (Figure 1). When observed in thin sections these shells are concentric circles with diameters between 10 and 40 μm, the circles simply resulting from planar sections through the concentric spheres centered around the inclusions [*Gentry*, 1973].

Many years of subsequent investigations have established that the radii of the concentric circles of the radiohalos as observed in thin sections are related to the α-decay energies. This enables the radioisotopes responsible for the α-decays to be identified [*Gentry*, 1974, 1984, 1986, 1988; *Snelling*, 2000]. Most importantly, when the central inclusions, or radiocenters, are very small (about 1 μm) the radiohalos around them have been unequivocally demonstrated to be products of the α-emitting members of the ^{238}U and the ^{232}Th decay series. The radii of the concentric multiple spheres, or rings in thin sections, correspond to the ranges in the host minerals of the α-particles from the α-emitting radioisotopes in those two decay series [*Gentry*, 1973, 1974, 1984]

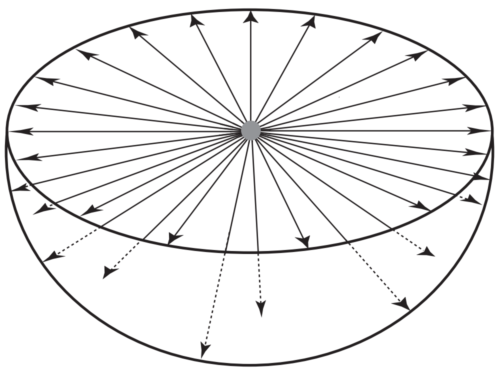


Figure 1. Sunburst effect of α-damage trails. The sunburst pattern of α-damage trails produces a spherically colored shell around the halo center. Each arrow represents approximately 5 million α-particles emitted from the center. Halo coloration initially develops after about 100 million α-decays, becomes darker after about 500 million, and very dark after about 1 billion (after *Gentry* [1988]).

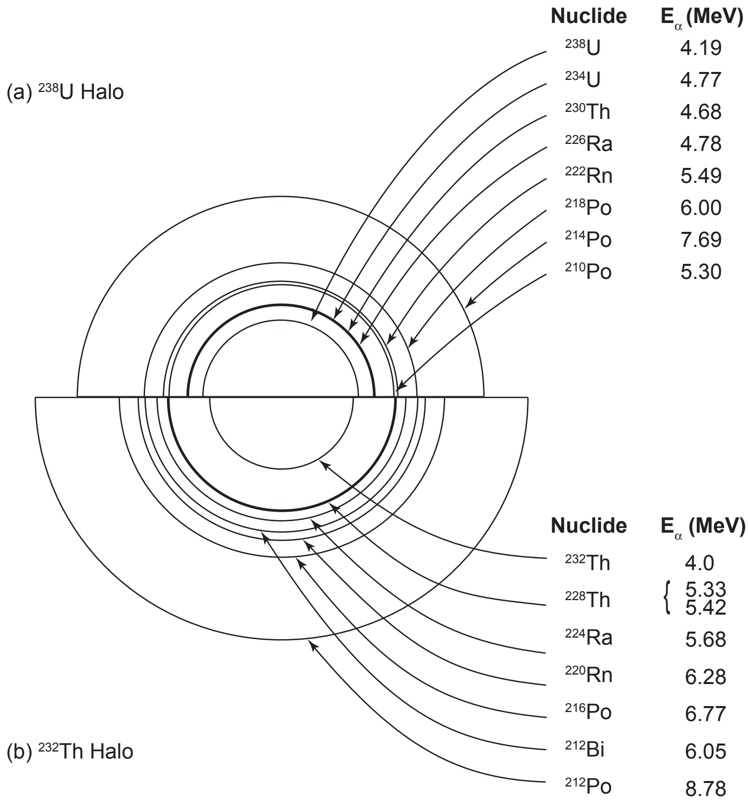


Figure 2. Schematic drawing of (a) a ^{238}U halo, and (b) a ^{232}Th halo, with radii proportional to the ranges of α-particles in air. The nuclides responsible for the α-particles and their energies are listed for the different halo rings (after *Gentry* [1973]).

(Figure 2). Uranium-235 radiohalos have not been observed. This is readily accounted for by the scarcity of ^{235}U (only 0.7% of the naturally-occurring U), since large concentrations of the parent radionuclides are needed to produce the concentric ring structures of the radiohalos.

Ordinary radiohalos can be defined, therefore, as those that are initiated by ^{238}U or ^{232}Th α-decay, irrespective of whether the actual halo sizes closely match the respective idealized patterns (Figure 2). In many instances the match is very good, the observed sizes agreeing very well with the ^{4}He ion penetration ranges produced in biotite, fluorite and cordierite [*Gentry*, 1973, 1974]. Uranium and Th radiohalos usually are found in igneous rocks, most commonly in granitic rocks and in granitic pegmatites. While U and Th radiohalos have been found in over forty minerals, their distribution within these minerals is very erratic [*Ramdohr*, 1933, 1957, 1960; *Stark*, 1936]. Biotite is quite clearly the major mineral in which U and Th radiohalos occur. Wherever found in biotite they are prolific, and are associated with tiny zircon (U) or monazite (Th) radiocenters. The ease of thin section preparation, and the clarity of the radiohalos in these sections, have made biotite an ideal choice for numerous radiohalo investigations, namely, those of *Joly* [1917a, b, 1923, 1924], *Lingen* [1926], *Iimori and Yoshimura* [1926], *Kerr-Lawson* [1927, 1928], *Wiman* [1930], *Henderson and Bateson* [1934], *Henderson and Turnbull* [1934], *Henderson et al.* [1934], *Henderson and Sparks* [1939], *Gentry* [1968, 1970, 1971], and *Snelling and Armitage* [2003]. Uranium, Th and other specific halo types in most of these studies have been observed mainly in Precambrian rocks, so much remains to be learned about their occurrence in rocks from the other geological periods of the strata record. However, some studies have shown that they do exist in rocks stretching from the Precambrian to the Tertiary [*Holmes*, 1931; *Stark*, 1936; *Wise*, 1989; *Snelling and Armitage*, 2003]. Unfortunately, in most instances the radiohalo types are not specifically identified in these studies.

Some unusual radiohalo types that appear to be distinct from those formed by ^{238}U and/or ^{232}Th α-decay have been observed [*Gentry*, 1970, 1971, 1973, 1984, 1986; *Gentry et al.*, 1973, 1976a, 1978; *Snelling*, 2000]. Of these, only the Po (polonium) radiohalos can presently be identified with known α-radioactivity [*Gentry*, 1967, 1968, 1973, 1974; *Gentry et al.*, 1973, 1974]. There are three Po isotopes in the ^{238}U-decay chain. In sequence they are ^{218}Po (half-life of 3.1 minutes), ^{214}Po (half-life of 164 microseconds), and ^{210}Po (half-life of 138 days). Polonium halos contain only rings produced by these three Po α-emitters (Figure 3). They are designated by the first (or only) Po α-emitter in the portion of the decay sequence that is represented. The presence in Po radiohalos of only the rings of the three Po α-emitters implies that the radiocenters

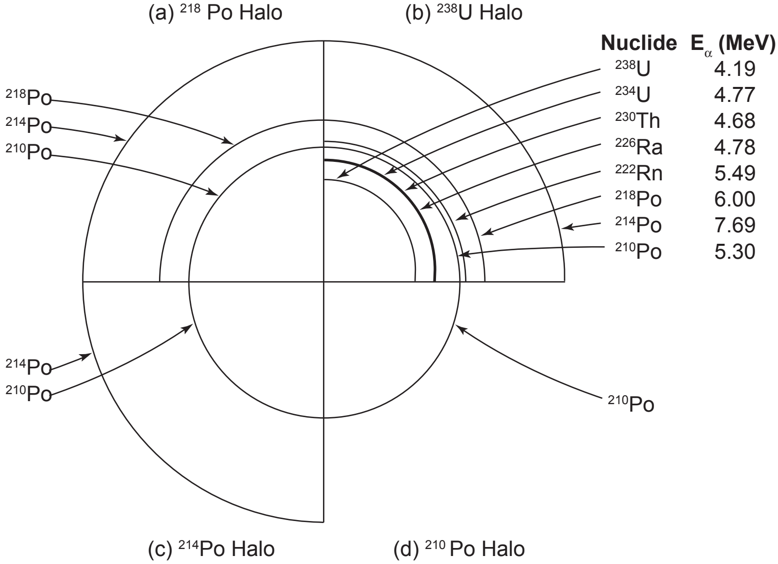


Figure 3. Composite schematic drawing of (a) a ^{218}Po halo, (b) a ^{238}U halo, (c) a ^{214}Po halo, and (d) a ^{210}Po halo, with radii proportional to the ranges of α-particles in air. The nuclides responsible for the α-particles and their energies are listed for the different halo rings (after *Gentry* [1973]).

which produced these Po radiohalos initially contained only either the respective Po radioisotopes that then parented the subsequent α-decays, or a non-α-emitting parent [*Gentry*, 1971; *Gentry et al*., 1973]. These three Po radiohalo types occur in biotites within granitic rocks [*Gentry*, 1968, 1971, 1973, 1974, 1984, 1986, 1988; *Gentry et al*., 1973, 1974; *Wise*, 1989; *Snelling and Armitage*, 2003].

Joly [1917b, 1924] was probably the first to investigate ^{210}Po radiohalos and was clearly baffled by them. Because *Schilling* [1926] saw Po radiohalos located only along cracks in fluorite from Wölsendorf in Germany, he suggested that they originated from preferential deposition of Po from U-bearing solutions. *Henderson* [1939] and *Henderson and Sparks* [1939] invoked a similar but more quantitative hypothesis to explain Po radiohalos along conduits in biotite. However, those Po radiohalos found occurring along much more restricted cleavage planes, similar to those found by *Gentry* [1973, 1974], have been more difficult to account for. The reason for these attempts to explain the origin and formation of the Po radiohalos by some secondary process is simple—the half-lives of the respective Po isotopes are far too short to be reconciled with the Po having been primary, that is, originally in the granitic magmas which are usually claimed to have slowly cooled to form the granitic rocks that now contain the Po-radiohalo-bearing biotites. The half-life of ^{218}Po, for example, is 3.1 minutes. However, this is not the only formidable obstacle for any secondary process that transported the Po into the biotites as, or after, the granitic rocks cooled. First, there is the need for isotopic separation of the Po isotopes, or their β-decay precursors, from parent ^{238}U [*Gentry et al.*, 1973]. Second, the radiocenters of very dark ^{218}Po radiohalos, for example, may need to have contained as much as 5×10^9 atoms (a concentration of greater than 50%) of ^{218}Po [*Gentry*, 1974]. But these ^{218}Po atoms must migrate or diffuse from their source at very low diffusion rates through surrounding mineral grains to be captured by the radiocenters before the ^{218}Po decays [*Fremlin*, 1975; *Gentry*, 1968, 1975].

Studies of some Po radiohalo centers in biotite (and fluorite) have shown little or no U in conjunction with anomalously high ^{206}Pb/^{207}Pb and/or Pb/U ratios, which would be expected from the decay of Po without the U precursor that normally occurs in U radiohalo centers [*Gentry*, 1974; *Gentry et al.*, 1974]. Indeed, many ^{206}Pb/^{207}Pb ratios were greater than 21.8 reflecting a seemingly abnormal mixture of Pb isotopes derived from Po decay independent of the normal U-decay chain [*Gentry*, 1971; *Gentry et al.*, 1973]. Thus, based on these data, Gentry advanced the hypothesis that the three different types of Po radiohalos in biotites represent the decay of primordial Po (that is, original Po not derived by U-decay), and that the rocks hosting these radiohalos, that is, the Precambrian granites as he perceived them all to be, must be primordial rocks produced by fiat creation, given that the half-life of ^{214}Po is only 164 microseconds [*Gentry*, 1979, 1980, 1982, 1983, 1984, 1986, 1988, 1989].

As a consequence of Gentry's Creation hypothesis, the origin of the Po radiohalos has remained controversial and thus apparently unresolved.

Snelling [2000] has thoroughly discussed the many arguments and evidences used in the debate that has ensued over the past two decades, and concluded that there were insufficient data on the geological occurrence and distribution of the Po radiohalos for the debate to be decisively resolved. Of the twenty-two locations then known where the rocks contained Po radiohalos, *Wise* [1989] had determined that six of the locations hosted Phanerozoic granitic rocks, a large enough proportion to severely question Gentry's hypothesis of primordial Po in fiat created granitic rocks. Many of these Po radiohalo occurrences are also in proximity to higher than normal U concentrations in nearby rocks and/or minerals, suggesting ideal sources for fluid separation and transport of the Po. Furthermore, *Snelling* [2000] found that there are now significant reports of ^{210}Po as a detectable species in volcanic gases, in volcanic/hydrothermal fluids associated with subaerial volcanoes and fumeroles, and associated with mid-ocean ridge hydrothermal vents and chimney deposits [*LeCloarec et al*., 1994; *Hussain et al*., 1995; *Rubin*, 1997], as well as in groundwaters [*Harada et al*., 1989; *LaRock et al*., 1996]. The distances involved in this fluid transport of the Po are several kilometers (and more), so there is increasing evidence of the potential viability of the secondary transport of Po by hydrothermal fluids during pluton emplacement, perhaps in the waning stages of the crystallization and cooling of granitic magmas [*Snelling and Woodmorappe*, 1998; *Snelling*, 2000]. Indeed, as a result of this present study, *Snelling and Armitage* [2003] investigated the Po radiohalo occurrences in three Phanerozoic granitic plutons and logically argued for a model of Po radiohalo formation involving secondary transport of Po by hydrothermal fluids during crystallization and cooling of the granitic magmas. Their data from the present study and details of this hydrothermal fluid transport model have been published [*Snelling et al*., 2003], but full details encompassing these results will be elaborated upon in this report.

Whereas Po radiohalos would appear to indicate extremely rapid geological processes were responsible for their production (because of the extremely short half-lives of the Po isotopes responsible), ^{238}U and ^{232}Th radiohalos appear to be evidence of long periods of radioactive decay, assuming decay rates have been constant at today's rates throughout earth history. Indeed, it has been estimated that dark, fully-formed U and Th radiohalos require around 100 million years worth of radioactive decay at today's rates to form [*Gentry*, 1973, 1974; *Humphreys*, 2000; *Snelling*, 2000]. Thus the presence of mature U and Th radiohalos in granitic rocks globally throughout the geological record would indicate that at least 100 million years worth of radioactive decay at today's rate has occurred during earth history. As proposed by *Humphreys* [2000] and *Vardiman et al.* [2000], these observable data require that within the Biblical young-earth time framework radioisotope decay therefore had to have been accelerated, but just by how much needs to be determined. If, for example, mature U and Th radiohalos were found in granitic rocks that were demonstrated to have formed during the Flood year, then that would imply about 100 million years worth of radioisotope decay at today's rates had occurred at an accelerated rate during the Flood year [*Baumgardner*, 2000; *Snelling*, 2000]. Furthermore, if Po radiohalos were alongside U and Th radiohalos in the same Flood-related granitic rocks, then that would have implications as to the rate of formation and age of these granitic rocks formed during the Flood year within the Biblical timescale. Similarly, there is insufficient data on the distribution of all radiohalo types in the vast Precambrian geological record. Indeed, the distribution pattern of all radiohalo types in Precambrian granitic rocks might well be significant, providing clues about the earth's early history within the Biblical framework.

2. Rationale of the Present Study

A systematic effort was initiated to investigate the occurrence and distribution of all radiohalo types in granitic rocks throughout the geological record globally [*Vardiman et al.*, 2000]. The initial focus was on granitic plutons that intrude strata interpreted as having been deposited during the Flood, the plutons themselves thus being considered to have formed also during the Flood. In conventional terms these are granitic plutons that are designated as Paleozoic (Cambrian-Permian) and Mesozoic (Triassic-Cretaceous). As a picture began to emerge of the occurrence and distribution of all radiohalo types in those granitic rocks, investigations were then extended to also focus on Precambrian granitic rocks. These are interpreted as having formed during the pre-Flood era, some perhaps even being remnants of the Creation week itself. Some more recent granitic rocks, belonging to the Tertiary of the geological record, which tentatively represent post-Flood granitic intrusions, were also studied. Because the U and Th radiohalos are a physical record of α-decay of U and Th, and of how much α-decay has occurred, it was important to use in this study samples of granitic rocks from as many different levels in the geological record as possible to be representative of the full span of earth history, to thus obtain the best detailed overview of the history of radioisotope decay through the geological record. Furthermore, because the Po radiohalos have the potential to be direct physical evidence of rapid geological processes, it is crucial to know their distribution in the geological record. If the model for Po radiohalo formation by secondary transport of Po in hydrothermal fluids during the cooling of intruded granitic magmas [*Snelling and Armitage*, 2003] is sustained by all the relevant evidence, then that would not only have time implications for the intrusion and cooling of granitic magmas during the Flood, but also potentially throughout the other periods of earth history.

The advantage of radiohalos is not only do they represent a visible, physical record of nuclear decay, but that record is wiped away if a rock recrystallizes or if subsequent to its initial formation the rock is heated again to above the temperature at which previously-formed radiohalos are annealed. This means that the problem of inheritance of parent/daughter correlations (radioisotope ratios) that complicates standard isochron methods is avoided, and the radiohalos only record the nuclear decay that has occurred since the last heating event to which the host rocks were subjected. This has direct implications for Precambrian (pre-Flood) granitic rocks, because it is highly likely that many of them could have been reheated during the Flood due to the tectonic upheavals and the catastrophic deposition of thick sequences of sedimentary strata on those crystalline basement rocks. Should there be an absence of mature (fully-formed) U and Th radiohalos in

Phanerozoic granitic rocks, this would present a powerful argument that very little nuclear decay has taken place since multi-celled life was buried and fossilized at the onset of the Flood year. Ages of hundreds of millions of years as commonly determined by the standard radioisotope isochron methods could thus primarily be a consequence of inheritance of parent/daughter correlations (radioisotope ratios) from Precambrian sources in the earth's crust and mantle. On the other hand, if mature U and Th radiohalos are present in granitic rocks that were intruded, crystallized and cooled during the Flood year, then that would be direct physical evidence that at least 100 million years worth (at today's rates) of nuclear decay must have occurred during the Flood year only 4500 or so years ago, implying that the nuclear decay rates had to have been accelerated. Thus all types of radiohalos, wherever found in the granitic rocks of the geological record, have the potential to place constraints and implications on the history of nuclear decay through the earth's history, and to place time constraints upon the intrusion and cooling of granitic rocks and associated geological processes. This may also include time constraints on the sedimentary rocks that have been metamorphosed, some of those being so affected by the increasing temperatures and pressures that their metamorphism generated granitic magmas which subsequently crystallized *in situ* and cooled as the temperatures and pressures decreased again.

3. Collection of Samples

Granitic rocks are of course ubiquitous in the earth's crust and are frequently exposed at the earth's surface across large areas. Ease of access to suitable outcrops of granitic rocks is not uniform, so it was logical to target regions with easy access in proximity to those involved in the sampling program. Suitable Phanerozoic granitic rocks are well exposed in outcrops throughout southeastern Australia in the Lachlan, New England and Adelaide Fold Belts (Orogens) and are readily accessible in road cuts along the major highways linking the major cities of Brisbane, Sydney, Melbourne, and Adelaide, as well as along subsidiary roads branching from them. The conventional ages of these granitic rocks are Ordovician to Triassic, so to supplement the conventional timespan covered by those granitic rocks, samples were collected of the Cretaceous granitic rocks that outcrop extensively and are readily accessible in the Peninsular Ranges of southern California east and northeast of San Diego, as well as in the Sierra Nevada Ranges of the Yosemite area of central California. Precambrian granitic rocks were also sampled in the Grand Canyon along the Colorado River corridor accessed by raft. With the assistance of others, samples of other Precambrian and Phanerozoic granitic rocks were collected in Western Australia, Arizona, New Mexico, Colorado, Wyoming, Georgia, and North and South Carolina in the U. S. A., in Cornwall and the Lake District of England, and in parts of Scandinavia. Cretaceous and Tertiary granites were also sampled in Washington state, Montana, Idaho, Utah, and Arizona. Both the geographical coverage of these many samples, and their span of the geological record, provided an excellent representative sample set for the purposes of this study.

The space limitations of this report preclude a detailed description of each granitic pluton sampled, and of the samples collected for this study. Descriptions of three sampled granitic plutons and the results of the search for radiohalos in those samples have already been reported by *Snelling and Armitage* [2003]. The details of other selected granitic plutons sampled and the significance of the radiohalos found in them will be reported in other papers published elsewhere. For the purposes of this report the focus is on the overall study of the radiohalos found in all the granitic rock samples collected, so only general sample location details need to be provided. Of course, the key component of these granitic rocks for this study was the presence of biotite in them visible to the naked eye, and if possible trace amounts of zircon.

Most of the samples were obtained from road cuts through outcrops of granitic plutons along highways and subsidiary roads, but a few were collected along hiking trails, and in the case of the Grand Canyon, along the Colorado River corridor. Every effort was made to obtain the freshest samples. Fist-sized (1–2 kg) pieces of granitic rock were collected at each location, and when possible the details of the precise area sampled were recorded using a hand-held G. P. S. unit.

4. Experimental Procedures

A standard petrographic thin section was obtained for each sample. In the laboratory, a scalpel and tweezers were used to prize flakes of biotite loose from sample surfaces, or where necessary portions of the samples were crushed to liberate the constituent mineral grains. Biotite flakes were then hand-picked and placed on the adhesive surface of a piece of clear Scotch™ tape fixed to a bench surface with its adhesive side up. Once numerous biotite flakes had been mounted on the adhesive surface of this piece of clear Scotch™ tape, a fresh piece of clear Scotch™ tape was placed over them and firmly pressed along its length so as to ensure the two pieces of clear Scotch™ tape were stuck together with the biotite flakes firmly wedged between them. The upper piece of clear Scotch™ tape was then peeled back in order to pull apart the sheets composing the biotite flakes, and this piece of clear Scotch™ tape with thin biotite sheets adhering to it was then placed over a standard glass microscope slide so that the adhesive side had the thin mica flakes adhered to it. This procedure was repeated with another piece of clear Scotch™ tape placed over the original Scotch™ tape and biotite flakes affixed to the bench, the adhering biotite flakes being progressively pulled apart and transferred to microscope slides. As necessary, further hand-picked biotite flakes were added to replace those fully pulled apart. In this way tens of microscope slides were prepared for each sample, each with many (at least twenty to thirty) thin biotite flakes mounted on them. This is similar to the method pioneered by Gentry. A minimum of thirty (usually fifty) microscope slides was prepared for each sample to ensure good representative sampling statistics. Thus there was a minimum of 1000 biotite flakes mounted on microscope slides for each sample.

Each thin section for each sample was then carefully examined under a petrological microscope in plane polarized light and all radiohalos present were identified, noting any relationships between the different radiohalo types and any unusual features. The numbers of each type of radiohalo in each slide were counted by progressively moving the slide backwards and forwards across the field of view, and the numbers recorded for each slide were then tallied and tabulated for each sample. Only radiohalos whose radiocenters were clearly visible were counted. Because of the progressive peeling apart of many of the same biotite flakes during the preparation of the microscope slides, many of the radiohalos appeared on more than one microscope slide, so this procedure ensured each radiohalo was only counted once.

5. Results

All results have been compiled in three tables. Table 1 lists the results from all the Precambrian granites, Table 2 all the Paleozoic-Mesozoic granites, and Table 3 all the Tertiary granites. This grouping of samples was chosen as an approximation of what might constitute pre-Flood granitic rocks (the Precambrian granitic rocks of Table 1), Flood granitic rocks (the Paleozoic-Mesozoic granitic rocks of Table 2), and what tentatively might be designated as post-Flood granitic rocks (the Tertiary granitic rocks of Table 3). Some examples of typical radiohalos found in these granitic rocks are shown in the photomicrographs of Figure 4. Typically the U and Th radiohalos were found to be overexposed, that is, there has been so much α-decay of U and Th in the radiocenters that all the inner rings have been obliterated, so that all the areas inside the ^{218}Po and ^{216}Po rings respectively are dark (Figures 2 and 4). Similarly, in many of the samples the ^{210}Po radiohalos were also overexposed, clearly implying that there had been so much α-decay of the ^{210}Po in the radiocenters darkening all of the area inside the single ^{210}Po ring (Figures 3 and 4c). Even many of the ^{214}Po radiohalos in the samples in which they occur are overexposed, all of the area inside the ^{210}Po ring being darkened because of all the α-decay of ^{210}Po in the radiocenters (Figures 3 and 4f). However, the few ^{218}Po radiohalos observed in just a few samples (only in some of the Paleozoic-Mesozoic granitic rocks in Table 2) are all "normal" radiohalos, with all three Po rings visible (Figures 3 and 4g), except for the example in Figure 4h. Similarly, in some samples some of the ^{210}Po and ^{214}Po radiohalos are also "normal" (not overexposed) (Figure 4d and e).

A perusal of Tables 1, 2 and 3 unmistakably reveals that in most

Table 1. Radiohalos recorded in Precambrian (pre-Flood) granitic rocks.

Rock Unit	Location	"Age"	Samples (Slides)	Radiohalos					Number of Radiohalos per Slide	Number of Po Radiohalos per Slide	Ratios			
				^{210}Po	^{214}Po	^{218}Po	^{238}U	^{232}Th			^{210}Po:^{238}U	^{210}Po:^{214}Po	^{210}Po:^{218}Po	^{238}U:^{232}Th
Granite (Methrow)	Washington (USA)	600 Ma(?)	1 (50)	1	0	0	0	0	0.02	0.02	—	—	—	—
Pikes Peak Granite	Colorado (USA)	1080 Ma	1 (51)	80	2	0	8	0	1.8	1.6	10.0:1	40.0:1.0	—	—
Lake George Granite		1080 Ma	1 (51)	12	0	0	14	0	0.5	0.24	1.0:1.2	—	—	—
Sherman Granite	Wyoming (USA)	1400 Ma	1 (50)	4	0	0	0	0	0.1	0.1	—	—	—	—
Ruin Granite	Arizona (USA)	1430 Ma	1 (41)	176	1	0	10	0	4.6	4.3	17.6:1	176.0:1.0	—	—
Jemez granodiorite	New Mexico (USA)	1500 Ma	1 (33)	29	1	0	14	0	1.3	0.91	2.1:1	29.0:1.0	—	—
Granite (Unaweep Canyon)	Colorado (USA)	1500 Ma (?)	1 (50)	19	0	1	0	0	0.4	0.4	—	—	19.0:1.0	—
Orbicular granite (Shoup)	Idaho (USA)	1500 Ma	1 (50)	9	0	1	4	0	0.3	0.2	2.3:1	—	9.0:1.0	—
Helsinki Granite	Helsinki, Finland	1800 Ma	3 (150)	107	1	0	241	0	2.3	0.72	0.44:1	107.0:1.0	—	—
Ruby Pluton	Grand Canyon, Arizona (USA)	1716 Ma	3 (150)	486	0	0	16	0	3.35	3.24	30.4:1	—	—	—
Trinity Granodiorite		1730 Ma	3 (150)	74	2	0	0	0	0.5	0.5	—	37.0:1.0	—	—
Pipe Creek Pluton		1690–1740 Ma	1 (50)	132	0	0	0	0	2.6	2.6	—	—	—	—
Elves Chasm Granodiorite		1840 Ma	5 (250)	53	0	0	0	0	0.2	0.2	—	—	—	—
Owl Creek granite	Wyoming (USA)	2500 Ma	1 (50)	5	0	0	0	0	0.1	0.1	—	—	—	—
Namban Granite	Yilgarn (Western Australia)	2670–2689 Ma	1 (41)	318	16	0	120	3	10.7	8.15	2.7:1	19.9:1.0	—	40.0:1.0
Badja Granite			1 (43)	188	0	0	58	0	5.7	4.37	3.2:1	—	—	—
Rattlesnake granite	Wyoming (USA)	2800–2900 Ma	1 (50)	10	0	0	25	0	0.7	0.2	1.0:2.5	—	—	—
Bighorn granite			1 (50)	0	0	0	0	0	0	0	—	—	—	—
Granite (tonalite)	Ilomantsi, Finland	Archean	3(150)	85	0	0	0	0	0.6	0.6	—	—	—	—

Table 2. Radiohalos recorded in Paleozoic-Mesozoic (Flood) granitic rocks.

Rock Unit	Location	"Age"	Samples (slides)	Radiohalos					Number of Radiohalos per Slide	Number of Po Radiohalos per Slide	Ratios			
				^{210}Po	^{214}Po	^{218}Po	^{238}U	^{232}Th			^{210}Po:^{238}U	^{210}Po:^{214}Po	^{210}Po:^{218}Po	^{238}U:^{232}Th
Bitterroot Batholith	Idaho (USA)	70–90 Ma	4 (200)	38	0	0	18	0	0.28	0.19	2.1:1.0	—	—	—
Joseph Pluton, Idaho Batholith	Montana (USA)	70–90 Ma	1 (50)	0	0	0	0	0	0	0	—	—	—	—
Mt. Stuart Granite	Washington (USA)	88 Ma	1 (50)	0	0	0	0	0	0	0	—	—	—	—
Black Peak Batholith	Washington (USA)	Late Cretaceous	1 (50)	1	0	0	2	0	0.06	0.02	0.5:1.0	—	—	—
Golden Horn Granite			1(50)	7	0	0	1	0	0.2	0.14	7.0:1.0	—	—	—
Indian Hill granites	San Diego County, CA	90 Ma	4 (180)	279	11	0	45	0	1.86	1.61	6.2:1.0	25.4:1.0	—	—
La Posta Pluton		93 Ma	8 (383)	96	4	0	8	0	0.3	0.26	8.0:1.0	24.0:1.0	—	—
Granodiorite of Mono Dome	Yosemite, CA	93 Ma	1 (50)	6	0	0	0	0	0.1	0.1	—	—	—	—
San Jacinto Pluton	Palm Springs, CA	Late Cretaceous	9 (450)	96	0	0	9	0	0.22	0.21	10.7:1.0	—	—	—
Bass Lake Tonalite	Yosemite, CA	114 Ma	1 (50)	84	0	0	0	3	1.7	1.68	—	—	—	—
Ward Mountain Trondhjemite	Yosemite, CA	115 Ma	1 (50)	63	0	0	0	0	1.26	1.26	—	—	—	—
Granodiorite of Arch Rock	Yosemite, CA	114–117 Ma	2 (100)	106	0	7	10	0	1.23	1.13	10.6:1.0	—	15.1:1.0	—
Tonalite of the Gateway	Yosemite, CA	114–117 Ma	2 (100)	1	0	0	0	0	0.01	0.01	—	—	—	—
Wheeler Crest Granodiorite	Mammoth, CA	200–215 Ma	1 (50)	58	0	12	1	0	1.42	1.4	58.0:1.0	—	4.8:1.0	—
Lee Vining Canyon Granite	Yosemite, CA	200–215 Ma	1 (50)	108	0	2	13	0	2.46	2.2	8.3:1.0	—	54.0:1.0	—
Stanthorpe Adamellite	Qld, Australia	232 Ma	1 (48)	520	4	15	68	19	13.04	11.23	7.6:1.0	130.0:1.0	34.7:1.0	3.6:1.0

Table 2. (continued)

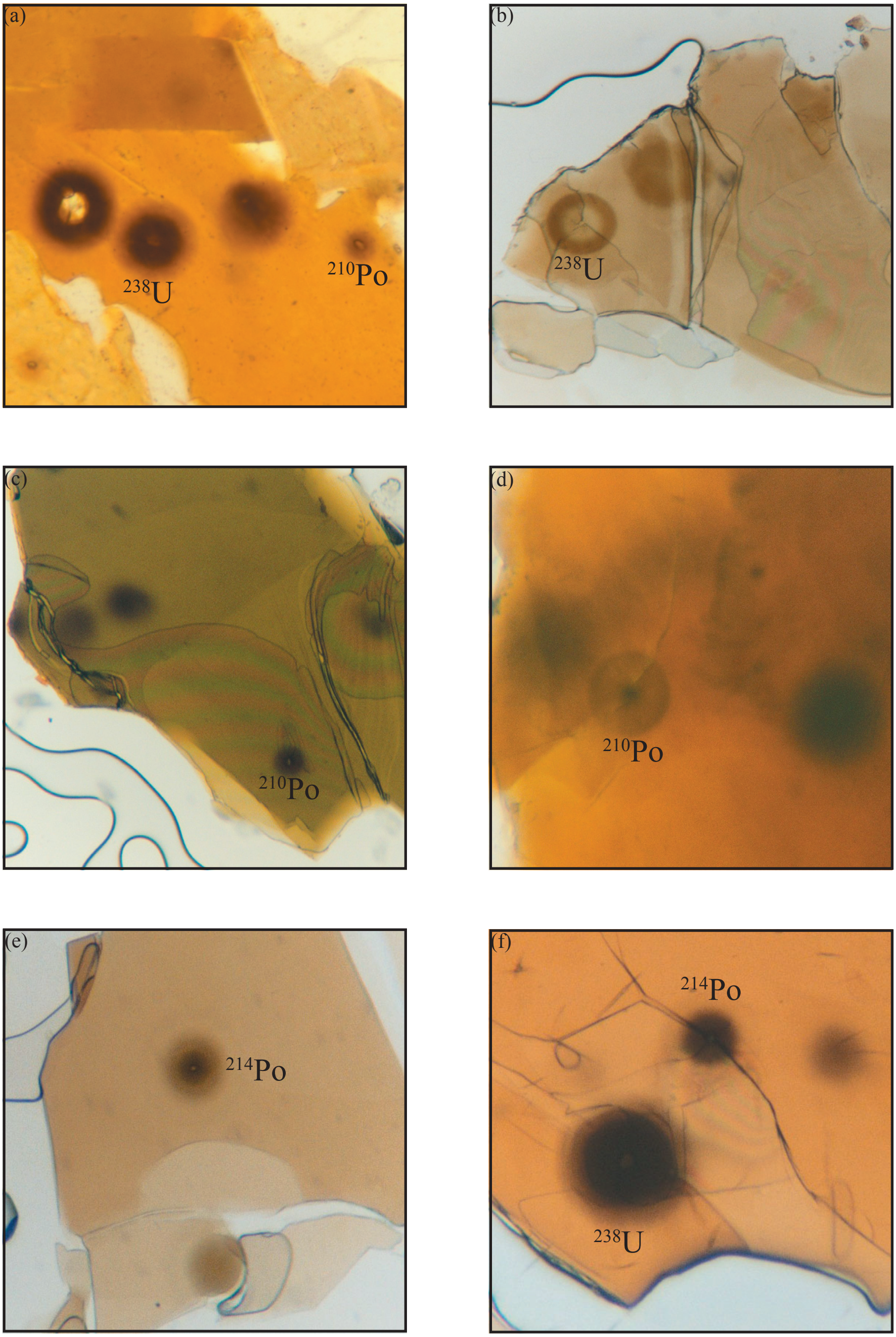
Rock Unit	Location	"Age"	Samples (slides)	Radiohalos					Number of Radiohalos per Slide	Number of Po Radiohalos per Slide	Ratios			
				^{210}Po	^{214}Po	^{218}Po	^{238}U	^{232}Th			^{210}Po:^{238}U	^{210}Po:^{214}Po	^{210}Po:^{218}Po	^{238}U:^{232}Th
Royken/Drammen Granite	Spikkestad, Norway	267±4 Ma	1 (100)	225	0	0	5	0	2.3	2.25	45.0:1.0	—	—	—
Finnamarka Granite	Gulsrudsetra, Norway	268±3 Ma	1 (50)	0	0	0	6	0	0.12	0	—	—	—	—
Land's End Granite	Cornwall, England	274 Ma	1 (32)	3307	485	27	5364	10	287.3	119.3	0.6:1.0	6.8:1.0	122.5:1.0	536.4:1.0
Stone Mountain Pluton	Atlanta, GA	291±7 Ma	6 (291)	1109	93	2	88	0	4.44	4.14	12.6:1.0	12.0:1.0	554.5:1.0	—
Liberty Hill Pluton	Lancaster, SC	299±48 Ma	3 (150)	180	0	0	0	0	1.2	1.2	—	—	—	—
Bathurst Granite	NSW, Australia	330 Ma	1 (51)	45	0	0	3	0	0.94	0.88	15.0:1.0	—	—	—
Spruce Pine pegmatites	Spruce Pine, NC	~340 Ma	3 (150)	1451	71	182	66	0	11.8	11.36	22.0:1.0	20.4:1.0	8.0:1.0	—
Mt Airy Granite	Mt Airy, NC	~350 Ma	2(100)	1271	22	0	120	0	14.13	12.93	10.6:1.0	57.8:1.0	—	—
Stone Mountain Granite	Stone Mountain, NC	~350 Ma	2(100)	1543	4	174	5	0	17.26	17.21	309.0:1.0	386.0:1.0	8.9:1.0	—
Harcourt Granite	Vic., Australia	369 Ma	1 (31)	107	130	0	198	0	14.03	7.65	1.0:1.5	1.0:1.2	—	—
Strathbogie Granite	Vic., Australia	374 Ma	1 (50)	1366	232	1	1582	10	63.82	31.98	1.0:1.2	5.9:1.0	1366.0:1.0	158.2:1.0
Shap Granite	Lake District, England	393 Ma	3 (157)	1334	14	4	394	41	11.38	8.61	3.4:1.0	95.0:1.0	333.0:1.0	9.6:1.0
Shannons Flat Granite	NSW, Australia	417–443 Ma	1 (101)	9	18	0	38	0	0.64	0.27	1.0:4.2	1.0:2.0	—	—
Jillamatong Granite	NSW, Australia	417–443 Ma	1 (31)	120	118	0	137	0	12.1	7.68	1.0:1.1	1.0:1.0	—	—
Cootralantra Granite	NSW, Australia	417–443 Ma	1 (43)	230	75	0	276	2	13.56	7.1	1.0:1.2	3.1:1.0	—	138.0:1.0
Cooma Granodiorite	NSW, Australia	433 Ma	1 (41)	373	44	0	418	37	21.27	10.17	1.0:1.1	8.5:1.0	—	11.3:1.0
Encounter Bay Granite	South Australia	487–490 Ma	1 (45)	362	8	0	1586	161	47.04	8.22	1.0:4.4	45.3:1.0	—	9.9:1.0
Palmer Granite	South Australia	490 Ma	1 (51)	1352	17	0	631	3	39.3	26.84	2.1:1.0	79.5:1.0	—	210.3:1.0

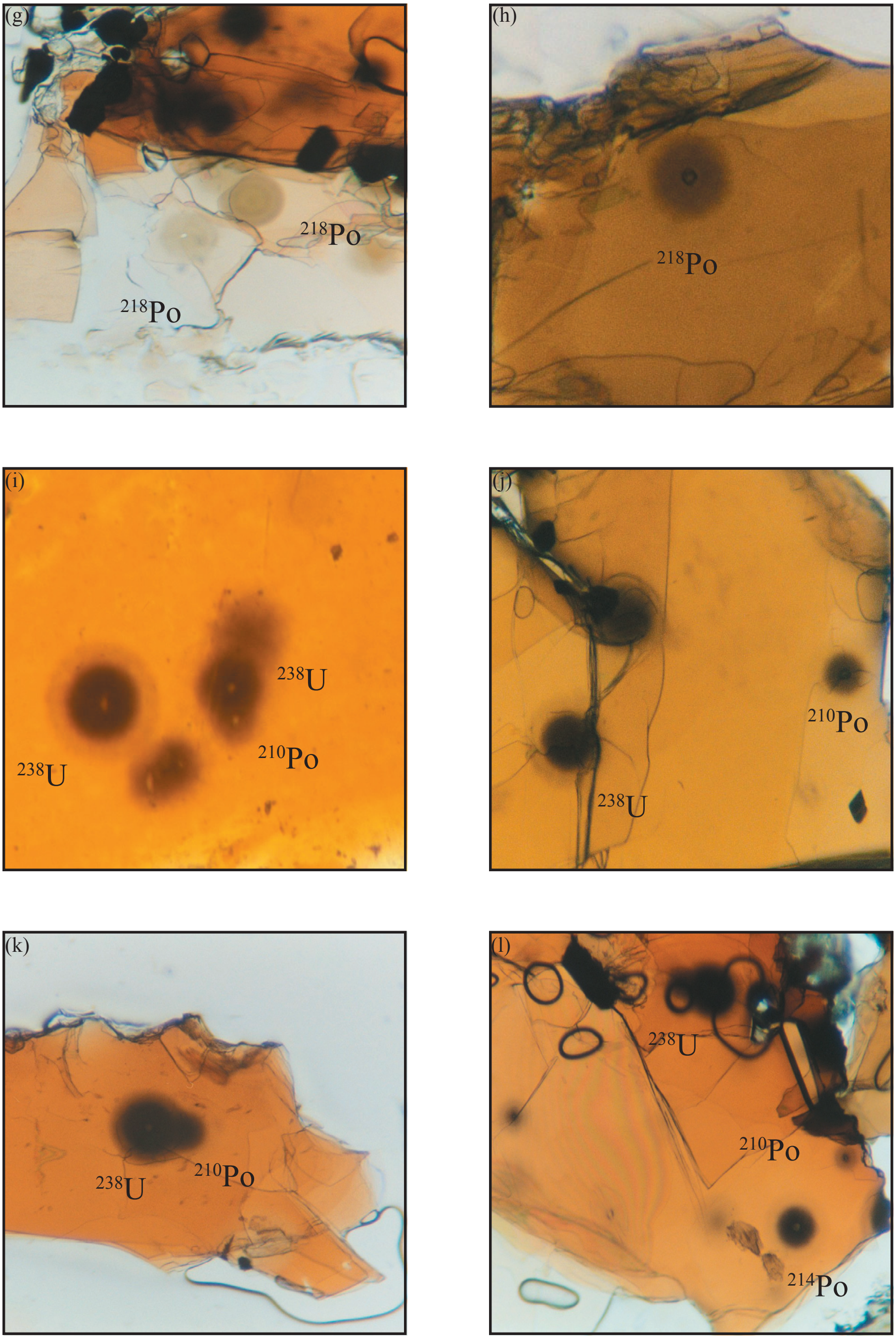
Table 3. Radiohalos recorded in Tertiary (tentatively post-Flood) granitic rocks.

Rock Unit	Location	"Age"	Samples (slides)	Radiohalos					Number of Radiohalos per Slide	Number of Po Radiohalos per Slide
				^{210}Po	^{214}Po	^{218}Po	^{238}U	^{232}Th		
Kingston Granite	Kingston Range, CA	Miocene	1 (50)	0	0	0	0	0	0	0
Granite	Phoenix, AZ	Early Miocene-Oligocene	1 (50)	0	0	0	0	0	0	0
Index Granite	Cascades, WA	Oligocene (33 Ma)	1 (50)	9	0	0	2	0	0.22	0.18
Spry Granite	Panguitch, UT	Oligocene	1 (50)	0	0	0	0	0	0	0
Granite	Salt Lake, UT	Tertiary	1 (50)	0	0	0	0	0	0	0
Chelan Granite	Pateros area, WA	Paleocene/ Cretaceous	2 (100)	0	0	0	0	0	0	0
Granite	Phoenix, AZ	Late Cretaceous/ Early Tertiary	1 (50)	0	0	0	0	0	0	0

samples prolific radiohalos were found, the number of ^{210}Po radiohalos often being very much greater than any other radiohalo type. As expected, all but one of the Tertiary granites in Table 3 contained no radiohalos, due undoubtedly to there having been insufficient time since these granitic rocks were intruded and cooled for enough α-decays to have accumulated enough damage to register as radiohalos (100 million years worth, at today's rates, of α-decays are regarded as being required to produce a mature, fully-formed ^{238}U radiohalo). Yet the sample from

Figure 4 (right). Some typical examples of the different radiohalos found in granitic rocks in this study. (a) An overexposed ^{238}U radiohalo (Cooma Granodiorite, diameter ~70 µm, center) and a ^{210}Po radiohalo (diameter ~39 µm, right). (b) A reversed ^{238}U radiohalo (Shap Granite, diameter ~70 µm). (c) An overexposed ^{210}Po radiohalo (migmatite adjacent to Palmer Granite, diameter 39 µm, lower right). (d) A normal ^{210}Po radiohalo (Stone Mountain Granite, diameter ~39 µm). (e) A normal ^{214}Po radiohalo (Encounter Bay Granite, diameter ~68 µm. (f) Another ^{214}Po radiohalo (centered on a crack) (Land's End Granite, diameter ~68 µm, right) and an overexposed ^{238}U radiohalo (diameter ~70 µm, left).


(a)
238U
210Po
(b)
238U
(c)
210Po
(d)
210Po
(e)
214Po
(f)
214Po
238U


(g)
^{218}Po
^{218}Po
(h)
^{218}Po
(i)
^{238}U
^{210}Po
^{238}U
(j)
^{210}Po
^{238}U
(k)
^{238}U
^{210}Po
(l)
^{238}U
^{210}Po
^{214}Po

the Index Granite in the Cascades region of Washington state, with a geological age of Oligocene and a radioisotope age of 33 Ma, contained two mature U radiohalos, which suggests that perhaps considerably less than 100 million years worth (at today's rates) of α-decays were needed to form them (or the granite may be older in conventional terms than currently designated/determined).

Another observation is that radiohalos appear to be more prolific in Paleozoic-Mesozoic (Flood) granitic rocks than in Precambrian (pre-Flood) granitic rocks. Because more than one sample was obtained from some granitic plutons and more slides were made from some samples than from others, there needs to be another way of comparing how prolific the radiohalos are in each sample than by looking at the absolute numbers of radiohalos listed in Tables 1 and 2. Thus in those tables appear two columns listing the numbers of radiohalos and Po radiohalos observed in each granitic rock per microscope slide. Thus the Precambrian granitic rocks yielded from 0 to 10.7 radiohalos per slide (per sample), with most samples yielding 1–5 radiohalos per slide (Table 1). On the other hand, the Paleozoic-Mesozoic (Flood) granitic rocks can be seen to have yielded from 0.01 to over 250 radiohalos per slide (per sample), with most samples yielding 1–12 radiohalos per slide (Table 2). These details are shown graphically in Figure 5. Similarly, the Precambrian (pre-Flood) granite rocks yielded from 0 to 8.15 Po radiohalos per slide (per sample) (Table 1), while the Paleozoic-Mesozoic (Flood) granitic rocks yielded from 0 to 119.3 Po radiohalos per slide (per sample) (Table 2). These details are also shown graphically in Figure 6. Perhaps the dataset is not yet large enough to be adamant,

Figure 4 (left). Some typical examples of the different radiohalos found in granitic rocks in this study. (g) Two faint normal ^{218}Po radiohalos (Land's End Granite, diameter ~70 mm, center). (h) An overexposed ^{218}Po radiohalo (Shap Granite, diameter ~70 mm). (i) Overexposed adjacent and overlapping ^{238}U and ^{210}Po radiohalos (Cooma Granodiorite). (j) Overexposed ^{238}U and ^{210}Po radiohalos in the same biotite grain (Encounter Bay Granite). (k) Overlapping overexposed ^{238}U and ^{210}Po radiohalos in the same biotite flake (Land's End Granite). (l) ^{238}U (upper center), ^{214}Po (lower right) and ^{210}Po (right) radiohalos together in the same biotite grain (Land's End Granite).

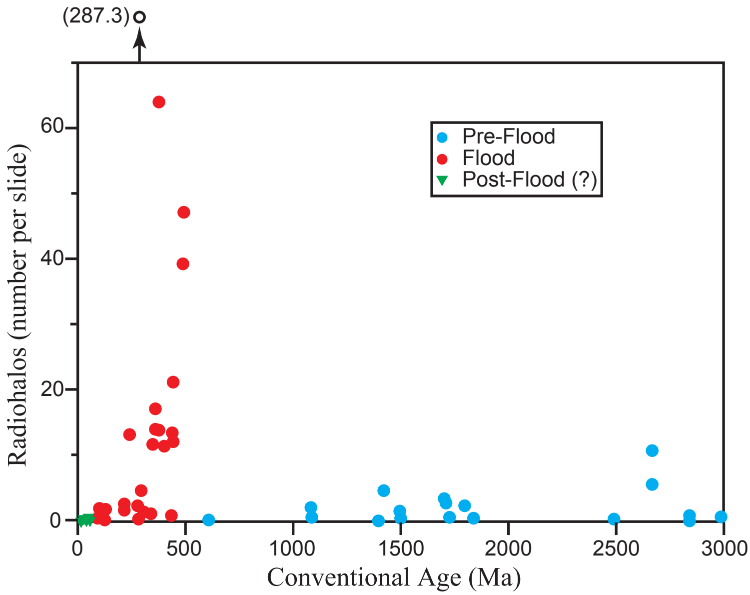


Figure 5. Plot of the conventional age (in millions of years) versus the total number of radiohalos per slide (per sample) for each granitic pluton listed in Tables 1, 2, and 3. The outlier of 287.3 radiohalos per slide is the Land's End Granite, Cornwall, England.

but from these data it would appear that all types of radiohalos are generally more prolific in Paleozoic-Mesozoic (Flood) granitic rocks, as is evident by the number of the granitic rocks in Table 2 containing more than 20 radiohalos per slide, many more than the Precambrian granitic rocks with the best radiohalo yield at just over 10 radiohalos per slide.

In most of these granitic rocks ^{210}Po radiohalos are more abundant than ^{238}U radiohalos (see the ratios columns in Tables 1 and 2). Generally, ^{210}Po radiohalos are 6–12 times more abundant than ^{238}U radiohalos. But there are higher and lower abundance ratios, and in some of these granitic rocks ^{238}U radiohalos are more prevalent than ^{210}Po radiohalos. There just does not seem to be any clear pattern that stands out. In some granitic rocks only ^{210}Po radiohalos are found. Indeed, all but one of the Paleozoic-Mesozoic (Flood) granitic rocks contain ^{210}Po radiohalos even when ^{238}U radiohalos are absent, whereas some of the Precambrian (pre-Flood) granitic rocks contain no radiohalos at all, even when tiny zircon crystals are included within the biotite flakes in them. It is likely, therefore, that ^{238}U radiohalos were originally present in those Precambrian granitic rocks but have since been annealed (that is, the α-particle damage was "healed" by subsequent heating of the rocks energizing the biotites' atoms to move back into their normal crystal lattice positions). Polonium-214 and ^{218}Po radiohalos are rare and only present in some of these granitic rocks (Tables 1 and 2). In the Paleozoic-Mesozoic (Flood) granitic rocks ^{214}Po radiohalos are often present, with or without ^{218}Po radiohalos. In two instances (Table 2) ^{214}Po radiohalos are more abundant than ^{210}Po radiohalos, but otherwise the latter outnumber the former generally by 5–40 to 1. Also, ^{210}Po radiohalos always outnumber the few ^{218}Po radiohalos that sometimes are present, with or without ^{214}Po radiohalos. When both ^{214}Po and ^{218}Po

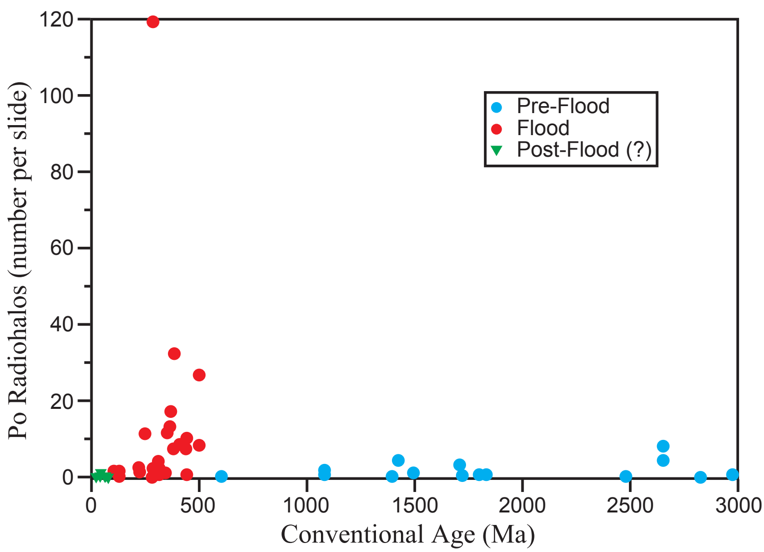


Figure 6. Plot of the conventional age (in millions of years) versus the number of Po radiohalos per slide (per sample) for each granitic pluton listed in Tables 1, 2, and 3. The 119.3 Po radiohalos per slide is again the Land's End Granite, Cornwall, England.

radiohalos are present the former always outnumber the latter, except in one instance, the Stanthorpe Adamellite (see Table 2). Consequently, there again does not appear to be a consistent pattern in the occurrence and abundances of the three Po radiohalo types. Furthermore, there does not appear to be any major difference in the pattern of occurrence of the three Po radiohalo types in the Precambrian (pre-Flood) granitic rocks compared to the Paleozoic-Mesozoic (Flood) granitic rocks, except that the Po radiohalos would seem to be more abundant in the Paleozoic-Mesozoic granitic rocks. Even the ^{238}U radiohalos appear to be more abundant in the Paleozoic-Mesozoic (Flood) granitic rocks compared to the Precambrian (pre-Flood) granitic rocks, even though tiny zircon grains would appear to be just as prevalent in all these biotite-bearing granitic rocks. Where ^{232}Th radiohalos occur surrounding monazite (thorium phosphate) inclusions, they are invariably and overwhelmingly outnumbered by the ^{238}U radiohalos around zircon inclusions.

6. Discussion

6.1 Pre-Flood and Flood Granites

Perhaps the most critical issue that needs to be first resolved is the question of the distinction between pre-Flood and Flood granites. This is particularly necessary in the light of Gentry's Creation hypothesis that, because of the brief half-lives of ^{218}Po and ^{214}Po, the granites in which these Po radiohalos are found must be primordial rocks produced by fiat creation [*Gentry*, 1979, 1980, 1982, 1983, 1984, 1986, 1988, 1989]. This claim has been regarded by many as justified, because most of the granitic rocks and related pegmatites and veins that yielded the Po radiohalos studied by Gentry are designated as Precambrian and thus recognized as pre-Flood, and maybe even Creation week when fiat creation did occur, as testified by the eyewitness account given by the Creator Himself in Genesis 1. The Precambrian designation of those granitic rocks is of course based on the observation that they intrude into, or are associated with, other Precambrian rocks, including Precambrian sedimentary strata and especially Precambrian metamorphic rocks. It is a moot point, but very much still under investigation and discussion, as to just how much of the Precambrian geologic record and the granitic rocks it contains should be consigned to the Creation week, and therefore how much of it pertains to the pre-Flood era from the end of the Creation week until the initiation of the Flood event. Even though some would place the pre-Flood/Flood boundary among the uppermost Precambrian (Upper Proterozoic) strata only a small distance below the Precambrian/Cambrian boundary [*Austin and Wise*, 1994], there is a widespread consensus that the evidence for the commencement of the Flood in the geologic record is where the strata containing fossilized multi-cellular organisms begin, and that is confirmed by the associated evidence of catastrophic deposition of those and other sedimentary strata. Thus the granitic rocks sampled and listed in Table 1 would be widely accepted as pre-Flood because they meet the necessary criteria for being so identified. The only exception might be the first listed granite, from Washington, U.S.A., because its radioisotope "age" could indicate that it formed very early in the Flood during and after the catastrophic deposition of fossiliferous sedimentary strata with similar or earlier "age" designations. This is of course based on the assumption that the radioisotope "age" provides a guide to the relative position of the dated rock unit in the geologic record. But in any case, there is some uncertainty as to the radioisotope "age" of this granite, and its relative position in its local geological context would favor its pre-Flood designation.

Not all the granitic rocks in which Gentry (and others) found Po radiohalos are designated as Precambrian. Tables 4 and 5 in *Snelling* [2000], which were extracted from *Wise* [1989], show that at only fifteen of the twenty-two localities where Po radiohalos had previously been found are those Po radiohalos designated as being hosted by Precambrian granitic and other rocks. Among the six localities listed where the Po radiohalos are hosted by conclusively-identified Phanerozoic granitic rocks is the Conway Granite of New Hampshire, which has been radioisotope dated as Jurassic [*Foland et al.*, 1971; *Foland and Faul*, 1977; *Foland and Allen*, 1991]. Indeed, the biotite flakes in which Gentry found the Po radiohalos had been separated by

Foland for the K-Ar radioisotope dating of the granite. As argued by *Wise* [1989] and *Snelling* [2000], the Conway Granite which hosts these Po halo-bearing biotite grains intrudes Paleozoic (or older Flood) schists and gneisses with distinct contact metamorphic zones, indicating that the host granite was hot when it intruded into the schists and gneisses. Furthermore, *Boucot et al*. [1958] had reported metamorphosed fossils in the schists and gneisses intruded by this granite, so undoubtedly these host rocks originally were fossiliferous Flood-deposited sediments that were subsequently metamorphosed and then intruded by this granite during the Flood (with nearly all fossils obliterated during the process). However, *Gentry* [1989] responded by suggesting that the granite is still a created rock dating back to the Creation week, and instead was tectonically intruded as a solid body into the schists and gneisses during the Flood, the contact metamorphic zone being produced by the heat and pressure generated during this tectonic movement, plus hot fluids from depth. In this way, even though Po radiohalos are found in the biotite in this granite which intrudes metamorphosed fossil-bearing sedimentary rocks, Gentry would still claim the granite and the Po were primordial (created). Indeed, *Gentry* [2003] argues that because the Scriptures repeatedly refer to God creating the foundations of the earth, and because deep drilling into the earth's crust at a number of sites has only found granitic rocks at such depths under the continents, granitic rocks must be the earth's foundation and therefore created by God. However, such an application of the Scriptures presumes the foundations of the earth have been correctly identified only as the granitic rocks at those depths in the earth's crust, when other rocks such as high-grade metamorphic granulites, which can be of granitic composition, have been demonstrated to occur at even greater depths in the earth's crust than where granitic rocks are found [*Müller*, 1977; *Wedepohl*, 1991, 1995]. Furthermore, the mantle rocks below could instead be interpreted as the foundation rocks of the earth implied by Scripture, because both the continents (continental crust) and the ocean basins (oceanic crust) sit on top of the mantle rocks.

To support his claim [*Gentry*, 2003] that all granitic rocks, as well as other hard crystalline rocks such as diorite, syenite, and gabbro, are all earth's primordial created rocks, Gentry has repeatedly challenged the geological community to synthesize granite in the laboratory containing biotite with Po radiohalos, all of which should be identical to the natural radiohalos, biotites and granites that he has studied from the various field locations [*Gentry*, 1979, 1983, 1984, 1986, 1988, 1989, 2003]. Gentry has maintained that if he is correct in identifying granitic rocks as primordial and created by God, then man will not be able to duplicate what God has created. Unfortunately, he has interpreted the apparent silence to his challenge as proving that granites have not been produced in laboratory experiments, and so the "parentless" Po radiohalos and the granites containing them did not form by natural processes. Nevertheless, *Wakefield* [1988b], *Wilkerson* [1989], *Wise* [1989], and *Snelling* [2000] have all responded with details of the experimental work that has been done to produce large crystals of the minerals found in granites, and also granitic textures, but Gentry continues to maintain that his challenge has never been, and therefore cannot be, met [*Gentry*, 2003]. However, as *Brown et al.* [1988] have pointed out, the ability to synthesize granite in the laboratory may have little to do with Creation, the argument basically being a *non sequitur*. Whether certain rocks or minerals can or cannot be synthesized in the laboratory may just reflect how sophisticated or not are laboratory procedures, equipment, etc. Indeed, minerals which could not be produced artificially in the past can now be synthesized—for example, diamonds and opals. Therefore, because all the basic minerals found in granites have already been synthesized in the laboratory [*Jahns and Burnham*, 1958; *Winkler and Von Platen*, 1958; *Mustart*, 1969; *Swanson et al.*, 1972], it would seem unwise to pose a challenge to the geological community on the basis of whether or not a hand-sized piece of granite is synthesized, since future developments in science are unpredictable. In any case, Gentry's insistence that his challenge has not been met is not only with respect to a piece of granite being produced in a laboratory, but the granite must contain Po radiohalos. However, the fact that the geological community has in general ignored Gentry's challenge is, in spite of continuing discussions over minor details, probably not due only to the geological community regarding the natural formation of granites by the crystallization and cooling of molten magma as already well proven from laboratory and field studies [*Pitcher*, 1993; *Hall*, 1996; *Johannes and Holtz*, 1996; *Bouchez et al.*, 1997; *Barbarin et al.*, 2001; *Best and Christiansen*, 2001], but because the Po radiohalos can be dismissed as a "very tiny mystery," as was done by Dalrymple in the 1981 Arkansas court case [*Gentry*, 1988, p. 122].

Even though some of the earliest Precambrian granites ultimately had to have been created by fiat during the Creation week with an automatic appearance of age, there is still the need to come to terms with those younger granites that were intruded into fossil-bearing and therefore Flood-deposited sedimentary strata, with all the appearance of clearly having formed as a result of the processes of intrusion of hot magmas that then crystallized and cooled. Granitic rocks listed in Table 2 fall into this category. So it is necessary to review the evidence that these granitic rocks have formed by the intrusion and cooling of hot magmas during the Flood, and that therefore the timescale for these processes is not in conflict with the timescale of the Flood event and the accumulation of its geological record. Indeed, it has already been shown by *Snelling and Woodmorappe* [1998] that it doesn't necessarily take long periods of time to form and cool large bodies of granitic rock. Furthermore, it is now clear that it previously was a misconception that the large crystals found in granitic rocks required slow cooling rates [*Wampler and Wallace*, 1998]. Indeed, the huge crystals sometimes found in granitic pegmatites indicate their rapid crystallization from fluids saturated with the components for those minerals.

6.2 Evidence for the Intrusion of Granitic Magmas

The experimental work on artificial silicate systems by *Tuttle and Bowen* [1958] is still regarded as a classic, groundbreaking study that settled the argument over the magmatic origin of granites. In the laboratory they melted powdered mixtures of the same compositions as natural granites and then allowed them to cool and crystallize. Significantly, the path of crystallization in the three-component system, quartz-orthoclase-albite (plagioclase), the three major mineral components of granitic rocks, reached its minimum temperature of 660–700°C when the components were in equal proportions (one-third each). When *Tuttle and Bowen* [1958] also plotted on triangular three-component compositional diagrams the normative mineral compositions (calculated from the whole-rock, major-element analyses) of 1269 granites and the modal compositions (as observed and determined from microscope thin sections) of 260 eastern U. S. granites, the quartz, orthoclase, and plagioclase percentages clustered around the small central areas of the diagrams representing a composition of one-third of each component. The point on the three-component compositional diagram where the minimum temperature plotted as the three minerals crystallized from the artificial molten magma in the laboratory coincided exactly with the tight clusters of both normative and modal analyses of the natural granites on the same diagram (the only slight variations being due to the use of different pressures and amounts of water in the laboratory experiments). The overwhelmingly obvious consensus was that these experiments had artificially reproduced natural granites from a hot granitic magma, and the strikingly unmistakable coincidence of the eutectic (minimum) point in the quartz-orthoclase-albite-water system with the exact normative and modal mineral compositions of thousands of granitic rocks analyzed then and subsequently, conclusively demonstrate that most natural granites must have therefore been derived by the cooling of hot granitic magmas. The granitic rocks listed in Table 2 have mineral compositions that are totally consistent with these results—for example, the Bathurst Granite [*Snelling*, 1974]. Lest it be argued that the grain sizes of the artificially produced granites are not exactly identical to those found in natural granites, it needs to be recognized that reproducing in the laboratory the natural conditions found inside the earth is extremely difficult because of their complexity, but many features of natural granites have been produced in the laboratory and it could only be a matter of time before granites absolutely identical to their natural counterparts are simulated in the laboratory. Most of the results of the experimental formation of granitic rocks and the application of those to the formation of natural granites have been compiled by *Johannes and Holtz* [1996].

In many sedimentary basins the deposited sediments with fossils buried in them can be thousands of meters thick. At depths of 5–10 km, especially in tectonically active zones, the pressures and temperatures can reach 5 kbar and 735°C respectively. Under those conditions, the phase equilibria laboratory studies [*Tuttle and Bowen*, 1958; *Johannes and Holtz*, 1996] have demonstrated that the fossiliferous sediments would partially melt, that is, the quartz (SiO_2), orthoclase ($KAlSi_3O_8$), and albite ($NaAlSi_3O_8$) components of the sediments melt leaving behind an unmelted residue of other components that have higher melting temperatures. Because the sedimentary rocks only partially melt to produce these three minerals in the melt, the result is that granitic (quartz-orthoclase-albite) magmas form. Granitic magmas are less dense than the surrounding residues and so, aided by the pressures at those depths, they then are forced to rise through fractures to intrude into the fossiliferous sediments near the top of the accumulated strata in the sedimentary basins, where they rapidly crystallize and cool [*Clemens and Mawer*, 1992; *Petford et al*., 1993, 2000; *Petford*, 1995; *Brandon et al*., 1996; *Harris et al*., 2000]. The specialists researching these processes have themselves been surprised by the evidence they are accumulating that the magma transport processes from the depths where melting has taken place to the shallow depths where the intrusions form are far more rapid than previously envisaged, and once intruded the crystallization and cooling processes are likewise extremely rapid because of the water content of the granitic magmas and because of the role of circulating groundwaters in convective flows into the plutons to carry the heat away [*Cathles*, 1977; *Spera*, 1982; *Ingebritsen and Hayba*, 1994; *Hayba and Ingebritsen*, 1997; *Snelling and Woodmorappe*, 1998]. Subsequent erosion (primarily at the end of the Flood) has exposed at the earth's surface these cooled granitic plutons intruded into the fossiliferous sediments that surround them. This relationship can be readily observed in the field for a number of the granitic plutons listed in Table 2—for example, the Bathurst Granite [*Snelling*, 1974], the Harcourt Granite, Shap Granite, and Encounter Bay Granite.

Regional relationships also provide evidence of the hot magmatic origin of granites. In the sedimentary basins where thick sequences of fossiliferous sediments accumulated rapidly during the Flood, the progressively deeper burial of these sedimentary strata resulted in them being subjected to increasing pressures and temperatures so that they were metamorphosed on a regional scale. As already indicated, when the temperatures and pressures reach critical levels at the highest grades of metamorphism partial melting begins to form granitic magmas. Of course, the fossils and any other organic material that were buried in these sediments were obliterated by the processes of regional metamorphism, so that eventually in the highest grade and partial melting zones all trace of them has gone. Nevertheless, because subsequent erosion at the end of the Flood may have eroded deeply into these rocks, it is now sometimes possible in the field to literally walk over the outcrops from the fossiliferous sedimentary rocks through the zones of progressively metamorphosed sedimentary rocks. The mineral constituents in these zones reflect the increasing temperatures and pressures of regional metamorphism, these temperatures and pressures being verified by many phase equilibria experiments [*Spear*, 1993; *Bucher and Frey*, 2002]. Walking further towards the center of the regional metamorphic complex one comes to where the felsic minerals (quartz, orthoclase, and plagioclase) in the metasedimentary rocks have melted to form migmatites (rocks in which *in situ* partial melting has caused segregation into separate bands within the rock of the felsic melt and mafic residues), and then finally to where the temperatures had been at around 735°C and pressures of 5 kbar and above, so that melting formed granitic rocks (with a mineral composition of approximately 30% quartz, 35% orthoclase, and 35% albite). Some of the granites listed in Table 2 are situated in just such a context with these regional relationships, the classic textbook example being the Cooma Granodiorite in the center of the Cooma Metamorphic Complex in southeastern Australia [*Hall*, 1996], as described and discussed by *Snelling and Armitage* [2003]. Other examples include the Stone Mountain Pluton and La Posta Pluton [*Snelling and Armitage*, 2003], and the Palmer Granite.

The local boundaries between granites and the rocks they have intruded also argue for a hot magmatic origin of granites. In the field, and in three dimensions within mines (both open cast and underground), the effects on the host rocks of the intrusion of hot granitic magmas can be observed, including veining, stoping (extensive veining so that blocks of host rock are surrounded and thus included in the granitic rock), and contact metamorphism. Unfortunately, however, outcrops of the contact zones are often poorly exposed or absent due to the alteration of both the margins of the granitic plutons and their immediately adjacent host rocks having facilitated deeper weathering of them. Nevertheless, where granite/host rock contacts are exposed there is abundant evidence of the effects on the host rocks of the intrusion of the hot granitic magmas. The most spectacular examples of such contact metamorphism are skarns, where granitic magmas have metamorphosed limestones to produce new minerals under the high temperature and pressure conditions consistent with the intruding granitic magmas being responsible, which have been verified by many phase equilibria experiments. Furthermore, in some instances the hot magmatic fluids from the granites have introduced metals into the resultant skarns, such as W at Grassy, King Island, Tasmania [*Kwak*, 1978a, b; *Wesoloski*, 1984; *Brown*, 1990] and Cu at Santa Rita, New Mexico [*Nielson*, 1970; *Ahmad and Rose*, 1980]. At the margins of the Bathurst Granite (Table 2) contact metamorphism of limestone has produced calc-silicate hornfels, with the contact zone between the granite and its host fossiliferous sedimentary strata exposed in outcrops, road cuts, and railroad cuttings, where veining, stoping, and late-stage granitic dikes vividly attest to the intrusion of the molten granitic magma [*Snelling*, 1974]. Some of these contact effects are also observable in outcrops at the margins of the Shap Granite and Encounter Bay Granite (Table 2).

Thus there is field evidence, both locally and regionally, that each of the granites listed in Table 2 was generated, intruded, crystallized, and cooled during the year-long catastrophic global Flood event. Space precludes describing and documenting in detail all the relevant field evidences for each listed granitic pluton, but these details for the Stone Mountain Pluton, the La Posta Pluton, and the Cooma Granodiorite have already been documented by *Snelling and Armitage* [2003].

Planned future papers will describe and document the field and other evidences for the generation and intrusion during the Flood of some more of the granites listed in Table 2—the Bathurst Granite, the Shap Granite, the Encounter Bay Granite, and the Palmer Granite. It is crucial here, though, to establish the Flood origin of these granitic plutons, because it then places time limits not only on the process of formation of these granitic plutons, but on the radiohalos contained in them and reported in Table 2. Indeed, some of the evidence that shows how the formation and cooling of granitic plutons could be achieved within the time limits of the Flood year has already been documented by *Snelling and Woodmorappe* [1998], while the radiohalo evidence that further constrains the time limits on the formation and cooling of granitic plutons to only days and weeks has been presented by *Snelling and Armitage* [2003], and *Snelling et al.* [2003].

6.3 The Po Radiohalo Formation Model

Snelling and Armitage [2003] proposed a hydrothermal fluid transport model for the secondary formation of the Po radiohalos. This model is shown schematically in Figure 7 (from *Snelling et al.* [2003]), and is described and explained in more technical detail in Appendix A.

Tiny zircon crystals containing ^{238}U are found included between the sheets in the biotite crystal structure. As the ^{238}U decays some of the ^{238}U decay products (^{222}Rn and the Po isotopes) diffuse out of the zircon crystals. These are then transported by hydrothermal fluids flowing along the cleavage planes between the biotite sheets distances of 1 mm or less to sites where the Po isotopes precipitate with S (or other) atoms. At temperatures above 150°C the α-tracks along the flow path are annealed and no ^{238}U or Po radiohalos form around either the zircon or the Po radiocenters respectively. However, once the temperature drops below 150°C, with continued hydrothermal fluid flow both ^{238}U and Po radiohalos form concurrently. The Po that α-decays in the Po radiocenters to form the radiohalos is replaced by more Po isotopes from the flowing hydrothermal fluids. Once the flow stops no further Po radiohalo development occurs.

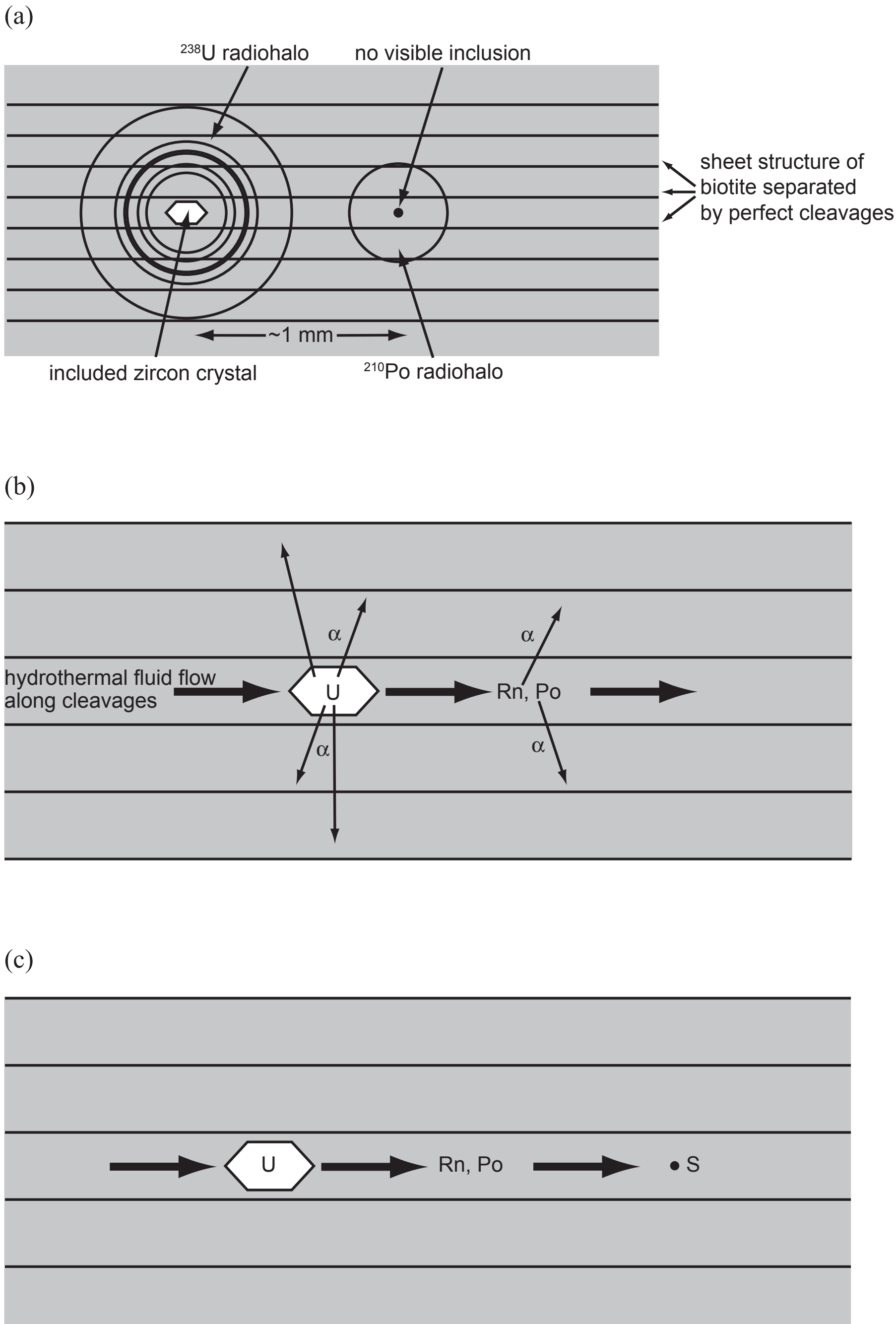
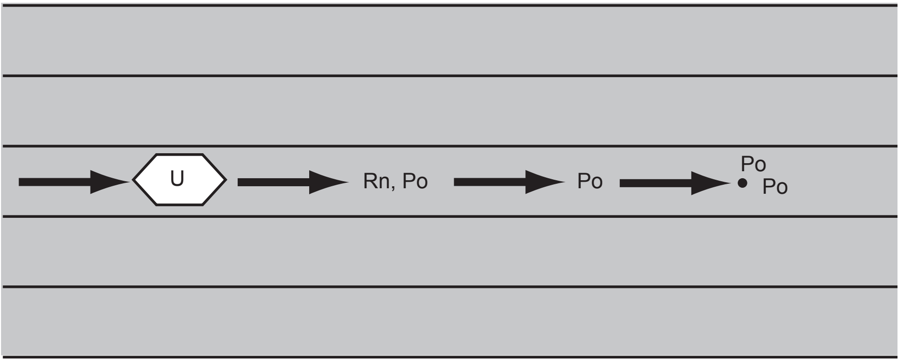

(a)
238U radiohalo
no visible inclusion
sheet structure of
biotite separated
by perfect cleavages
~1 mm
included zircon crystal
210Po radiohalo
(b)
hydrothermal fluid flow
along cleavages
α
α
U
α
α
Rn, Po
(c)
U
Rn, Po
S

Figure 7 (left). Time sequence of diagrams to show schematically the formation of ^{238}U and ^{210}Po radiohalos concurrently as a result of hydrothermal fluid flow along biotite cleavage planes. (a) Diagrammatic cross-section through a biotite flake showing the sheet structure and perfect cleavage. A tiny zircon crystal has been included between two sheets and its ^{238}U content has generated a ^{238}U radiohalo. A ^{210}Po radiohalo has also developed around a tiny radiocenter between the same two sheets. Its radiocenter contains no visible inclusion, being just a bubble-like "hole" left behind by loss of the inclusion, probably by dissolution of the solid phases. (b) Enlarged diagrammatic cross-section through a biotite flake that has crystallized from a granite magma to 300°C. The U in an included zircon crystal is emitting α-particles, while hydrothermal fluids released from the cooling magma are flowing along the cleavage plane dissolving Rn and Po decay products from the zircon and carrying them downflow where they also emit α-particles. (c) However, at temperatures >150°C the α-tracks are annealed, so no radiohalos form and there is no α-track record of the hydrothermal fluids containing Rn and Po flowing at a rate of up to 5 cm per day along the cleavage plane. A few S atoms are in lattice defects downflow of the zircon crystal.

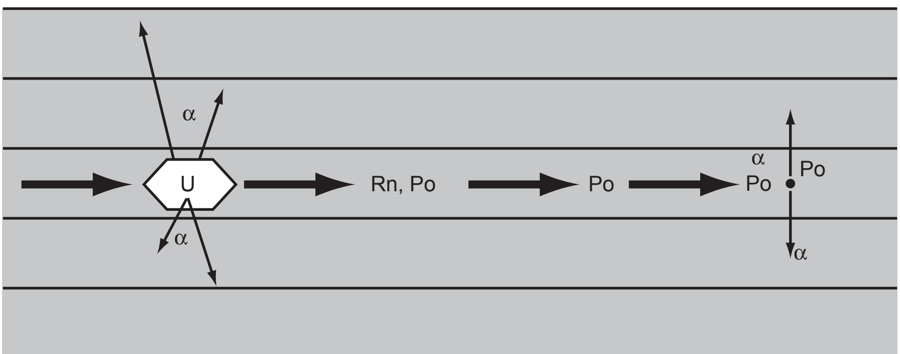
There are two important implications of this model. First, because of the short half-lives of the Po isotopes (only 3.1 minutes for ^{218}Po), the Po radiohalos had to form in a few hours to a few days. Second, because the full development of ^{238}U radiohalos requires the equivalent of at least 100 million years worth (at today's rates) of radioisotope decay, the concurrent formation of ^{238}U and Po radiohalos implies that at least 100 million years worth of radioisotope decay had to have occurred in no more than a few days. Thus radioisotope decay had to be accelerated, otherwise the decay of ^{238}U would not have supplied sufficient Po isotopes in the short time required to form the Po radiohalos. Furthermore, it can be demonstrated that all the processes involved in the model together place a limit of 6–10 days for the cooling of the host granitic plutons. All the technical details justifying these claims are in Appendix A.

Snelling and Armitage [2003] stressed that the secondary hydrothermal fluid transport model for the generation of the Po-rich radiocenters and subsequently the Po radiohalos was at that time tentative, awaiting

(d)



(e)



(f)

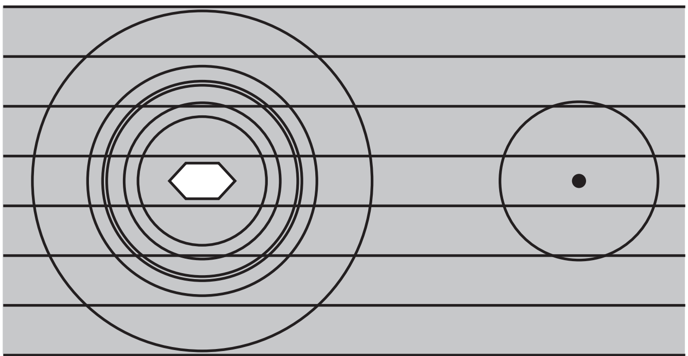


Figure 7 (left). Time sequence of diagrams to show schematically the formation of ^{238}U and ^{210}Po radiohalos concurrently as a result of hydrothermal fluid flow along biotite cleavage planes. (d) As the temperatures approach 150°C and ^{222}Rn decays to ^{218}Po, the Po isotopes in the hydrothermal fluids which have a geochemical affinity for S precipitate to form PoS as the fluids flow by the S in the lattice defects. The U in the zircon continues to decay and replenish the supply of Rn and Po in the fluids. (e) Once the temperature drops to below 150°C, the α-tracks produced by continued decay of U in the zircon and of Po in the PoS are no longer annealed and so start discoloring the biotite sheets. More Po isotopes in the flowing hydrothermal fluids replace the Po in the PoS as it decays to Pb, which also scavenges yet more Po. (f) With further passing of time and more α-decays both the ^{238}U and ^{210}Po radiohalos are fully formed, the granite cools completely and hydrothermal fluid flow ceases. Note that both radiohalos have to form concurrently below 150°C. The rate at which these processes occur must therefore be governed by the 138 day half-life of ^{210}Po. To get ^{218}Po and ^{214}Po radiohalos the processes would have to have occurred even faster.

further data collection and analysis. Their study reported results from only three granitic plutons, whereas this report provides the data from more than 50 granitic plutons ranging in conventional age from Archean to Tertiary (Tables 1, 2 and 3). These observations of the occurrence and distribution of the Po radiohalos in these granitic rocks are totally consistent with this secondary model for Po radiohalo formation. This model for Po radiohalo formation would also seem to be valid regardless of whether the granitic rocks are Precambrian (pre-Flood), Paleozoic-Mesozoic (Flood), or Tertiary (post-Flood?).

6.4 The Implications of the Annealing Temperature for Precambrian Granitic Rocks

The thermal annealing temperature of α-tracks and radiohalos is absolutely crucial to our understanding of the significance of all types of radiohalos, because it is only below that temperature that the radiohalos are preserved. Early observations on the annealing of radiohalos were based on heating experiments in the laboratory. *Poole*

[1928a, b] found that after fifteen minutes heating of both radiohalos and the host biotite at 610°C the halos had completely disappeared and the biotite very rapidly darkened. Similarly, *Armitage and Back* [1994] found that heating Po radiohalo-bearing biotite from 250° to 750°C for up to five hours causes variable but significant changes in damage to biotite, and can erase both structural defects and radiohalos. However, the most crucial and significant observations bearing on this question of the annealing temperature of radiohalos are those made in samples of granitic rocks taken from different depths in the deep drill-hole at Fenton Hill, New Mexico [*Laney and Laughlin*, 1981]. These observations are crucial because they involve granitic rocks under natural conditions. Uranium-238 radiohalos were found associated with every recognizable type of zircon inclusion in the biotite grains in the granitic rocks traversed by the drill-hole. The majority of the observed radiohalos were fully developed and somewhat overexposed. The present equilibrium down-hole temperatures were carefully measured and found to be 104°C at 870.8 m, 135.6°C at 1824.5 m, 153.7°C at 2164.7 m and 283°C at 4057.8 m. Zircons were found in the biotites throughout this temperature and depth range. Partial annealing of radiohalos was first observed at a depth of 1850 m (134°C present temperature). By a depth of 2120 m (151°C present temperature) the annealing of the radiohalos was total. Further down the hole there were zircon inclusions in the biotites as before, but the radiohalos had been totally annealed (obliterated). It was concluded that the present, elevated geothermal gradient had been sufficient to completely anneal the radiohalos at temperatures above about 150°C (at depths below 2115 m).

These observations are a guide to the temperature at which radiohalos are annealed under natural conditions. The temperature of 150°C is low from a geological perspective, and is towards the low end of the scale of temperatures over which hydrothermal fluids flowed in granitic rocks. All the samples of granitic rocks used in this study were collected from surface outcrops that aren't currently exposed to temperatures beyond 50°C, so the radiohalos found in them are not currently being annealed. However, it must be concluded, and this is crucial, that the radiohalos currently observed in these granitic rocks can only have formed and survived at temperatures below 150°C. A corollary to this is that if these granitic rocks have, since their formation, been subsequently exposed to temperatures of 150°C or greater, any radiohalos that were previously generated in them during or since their formation would have been annealed and obliterated during such a heating event.

The implications of these conclusions are highly significant, because they are fatal to Gentry's fiat Creation hypothesis for the origin of the Po radiohalos. Because the radiohalos we observe today, even in Precambrian granitic rocks, could only have formed since those rocks were last below 150°C, then the only circumstances under which currently observed radiohalos in Precambrian granitic rocks could have been generated at the time those rocks formed includes restriction of temperatures since their formation to less than 150°C. Such restriction would have to be regarded as not only highly improbable, but most likely impossible; because since their formation these Precambrian granitic rocks have usually been buried under thousands of meters of sediments deposited catastrophically during the global Flood event, subjecting them to elevated temperatures and pressures, particularly in tectonically active zones.

For example, the 1730–1840 Ma granitic rocks in the Precambrian crystalline basement of the Grand Canyon (Table 1) are estimated to have originally been buried under 3.5 km or more of Mesozoic-Paleozoic (Flood) sedimentary strata, and apatite fission track data indicate that these rocks were subjected to temperatures of at least 130–140°C [*Dumitru et al.*, 1994]. Indeed, apatite from a sample of the Elves Chasm Granodiorite yielded a fission track age of only a little more than 70 Ma [*Naeser et al.*, 1989] compared with that rock's zircon U-Pb radioisotope age of 1840 Ma [*Hawkins et al.*, 1996], indicating thermal annealing of the fission tracks in the apatite. Total annealing of fission tracks in apatite has been shown to occur at temperatures of between 105°C and 150°C [*Naeser*, 1981]. In the same drill-hole at Fenton Hill in New Mexico where the thermal annealing temperature of radiohalos was determined as being 150°C, it was found that the total annealing of fission tracks in apatite occurred at a temperature of 135°C [*Naeser and Forbes*, 1976]. However, equally significant is the zircon fission track data obtained from a granitic rock of the 1736 Ma Diamond Creek Pluton [*Karlstrom et al*., 2003], which together with three samples of the Middle Proterozoic Dox Formation that is older than the overlying 1100 Ma Cardenas Basalt [*Larson et al*., 1994; *Hendricks and Stevenson*, 2003], yielded a zircon fission track age of only 1038 Ma [*Naeser et al*., 1989]. This would indicate that zircon grains in the granitic rocks of the Grand Canyon's Precambrian crystalline basement were partially thermally annealed by their burial, even under Precambrian sedimentary rocks, prior to deposition of the overlying Paleozoic-Mesozoic (Flood) sedimentary rocks. The temperature at which fission tracks in zircons are totally annealed has been estimated at 200±40°C [*Harrison et al*., 1979; *Hurford*, 1985; *Zeitler*, 1985]. This implies that granitic rocks in the Precambrian basement of the Grand Canyon have been subjected to temperatures approaching 200°C since their formation. Consequently, even though these granitic rocks may have formed during the Creation week [*Austin*, 1994], the Po radiohalos currently observed in them (Table 1) cannot have been produced at that time, and thus are not (unfortunately) evidence of fiat creation.

It is highly likely, and almost certain, that the thermal history of the other granitic rocks listed in Table 1 is similar to that for the granitic rocks of the Grand Canyon's Precambrian crystalline basement. Indeed, the sample of Jemez granodiorite in Table 1 was obtained from the same deep drill-hole at Fenton Hill, New Mexico, in which *Laney and Laughlin* [1981] determined the annealing temperature of radiohalos. This sample came from a shallower depth than that at which the present temperature is 150°C. This does not imply that the ^{210}Po, ^{214}Po and ^{238}U radiohalos in this sample were generated at the time this granitic rock formed, contemporaneously with radiohalos in the same rock deeper in the drill-hole that have been obliterated by the current thermal regime. To the contrary, *Harrison et al*. [1986] found that ^{40}Ar/^{39}Ar analyses of microcline (potassium feldspar) from five samples of this 1500 Ma granodiorite, ranging in drill-hole depth from 1.13 to 4.56 km, and *in situ* temperatures from 110°C to 313°C, indicated thermal events affected the granodiorite at around 1030 and 870 Ma, well before the very recent development of the surrounding volcanic caldera responsible for the present geothermal gradient. The maximum $^{40}Ar/^{39}Ar$ age of 1030 Ma for the microcline grains from the 1500 Ma Jemez granodiorite was interpreted to represent the time at which the rock cooled below ~200°C [*Harrison and McDougall*, 1982], while the 870 Ma age was interpreted to be the time the regional temperature fell below about 130°C, perhaps because of a substantial amount of crustal uplift and erosion. This would appear to represent the earliest time since the formation of this granodiorite after which the ambient temperatures would be conducive to the radiohalos being generated also being preserved. But this doesn't take into account the granodiorite's subsequent burial by a sequence of Mesozoic and Paleozoic (Flood) sedimentary rocks [*Smith et al*., 1970] prior to the recent (post-Flood) volcanic activity responsible for the present geothermal gradient and the present annealing of radiohalos at depth. So again, a thorough investigation of the geological history and context of this Precambrian granitic rock reveals that the radiohalos presently observed in it are not related to the formation of the granitic rock, but were probably generated subsequently, during and after the Flood.

6.5 The Generation of the Present Po Radiohalos in Precambrian Granitic Rocks

However, if the Po radiohalos in these Precambrian granitic rocks (Table 1) were not generated at the time these granitic rocks formed, but were generated much later during and after the Flood, then how were they generated? It has already been shown that the secondary hydrothermal fluid transport model can explain the formation of Po radiohalos during the late stage of cooling of granitic rocks as they formed during the Flood, so if the Po radiohalos in these Precambrian (pre-Flood) granitic rocks were generated subsequent to, and much later than, the formation and cooling of these granitic rocks, then how could these Po radiohalos be generated? These questions can be simply answered by first determining from the earlier description what are the essential components of the secondary hydrothermal fluid transport model, and whether these components would still be present in these

Precambrian granitic rocks during the Flood.

The first requirement is the presence of zircons as a source of ^{222}Rn and Po isotopes from α-decay of the ^{238}U in them. The second requirement for modeling Po radiohalo formation is that the ^{238}U decay was accelerated, so that a very large quantity of ^{222}Rn and Po atoms would be generated in a very short time frame. The third requirement is flow of hydrothermal fluids through the granitic rocks, including along the biotite cleavage planes, to rapidly transport the ^{222}Rn and Po isotopes. And a fourth essential requirement is suitable Po deposition sites between the biotite cleavage planes. Throughout their existence these granitic rocks have had zircon grains containing ^{238}U and its decay products, and suitable sites for Po deposition between biotite cleavage planes. The zircon grains can still be seen in these granitic rocks under the microscope, as can the Po radiocenters around which Po radiohalos currently exist.

The missing essential component is flow of hydrothermal fluids. The present absence of hydrothermal fluids in these granitic rocks doesn't necessarily preclude their presence in these rocks at times subsequent to their formation, such as during the Flood event. Present-day hydrothermal systems on the ocean floors derive most of their hydrothermal fluids from seawater circulating through the permeable oceanic crust down into the hot rocks surrounding shallow magma chambers [*Scott*, 1997]. Similarly, groundwaters deep within sedimentary basins are heated and dissolve salts and metals to become hydrothermal fluids within the sedimentary strata themselves, and in the Precambrian crystalline basement rocks beneath [*Garven and Raffensperger*, 1997]. Indeed, it has been demonstrated by computer simulations that the warm basinal brines, which have scavenged U from sedimentary and volcanic strata, can become hydrothermal fluids that may penetrate along fracture zones down into the Precambrian crystalline basement beneath. Upon encountering reducing conditions there the U precipitates and concentrates as hydrothermal unconformity-type U deposits, which are high grade and account for more than 25 percent of the world's proven U reserves. There is much evidence that hydrothermal fluids can be generated in diverse geological environments; and that the water content of these fluids can be derived not only from magmatic sources, but also from ground and meteoric waters, and even during regional metamorphism [*Taylor*, 1997]. These relationships between the sources of hydrothermal fluids and the ore deposits the hydrothermal fluids have produced have been firmly established by oxygen and hydrogen isotope studies of the different water sources, and of fluid inclusions in minerals in ore deposits and other geological environments.

There are thus many potential sources of hydrothermal fluids to circulate through Precambrian granitic rocks subsequent to their initial formation and cooling. This would be particularly so during the global catastrophic Flood event, when many of these granitic rocks would have been buried under thick sequences of Flood-deposited sedimentary strata, and when catastrophic tectonics would have greatly accelerated and concentrated the flow of heat from the earth's mantle into the crust [*Austin et al.*, 1994]. Accelerated nuclear decay would have produced heat that augmented these catastrophic geological processes. This accelerated nuclear decay would have generated heat *in situ* at the sites within these Precambrian granitic rocks where ^{222}Rn and Po isotopes were being generated from ^{238}U in zircon grains within biotites. Renewed hydrothermal fluid flow would thus carry these isotopes along the biotite cleavage planes to replenish deposition sites with Po isotopes to form radiocenters and generate new Po radiohalos.

Indeed, there is evidence within these Precambrian granitic rocks of more than one period of hydrothermal fluid flow through them. For example, *Sasada* [1989] investigated the fluid inclusions within the quartz grains of the Jemez granodiorite in the drill-hole at Fenton Hill, New Mexico, and the fluid inclusions in calcite veins within the granodiorite. It was found that the fluid inclusions in both the calcite veins and the quartz grains in the Jemez granodiorite indicated a heating event involving hydrothermal fluids subsequent to formation and cooling of the granitic rocks, and this was followed by cooling and the formation of the calcite veins, before heating of the rocks again to the present temperature by the recent volcanic activity. Furthermore, it was found that the hydrothermal fluids responsible for precipitating the calcite veins in the waning stage of the earlier thermal event are probably similar to the present geothermal fluids in and around the Fenton Hill area of the Valles Caldera. Thus hydrothermal fluids were active in the Jemez granodiorite during a thermal event long after its formation, and the same hydrothermal fluids that deposited the calcite veins would have been capable of transporting ^{222}Rn and Po isotopes from zircon inclusions in biotite grains as they flowed along the biotite cleavage planes to then deposit the Po isotopes in radiocenters that generated new Po radiohalos, concurrently with the formation of new ^{238}U radiohalos around the zircon inclusions. It can therefore be demonstrated that the secondary hydrothermal fluid transport model for the generation of Po radiohalos applies to the Po radiohalos currently found in these granitic rocks. These radiohalos were most probably generated as a result of hydrothermal fluid flows during and after localized thermal events associated with the catastrophic global Flood, long after the granitic rocks and any original Po radiohalos had been formed and then annealed by subsequent thermal events.

6.6 Why the Variations in Abundances of the Radiohalos?

It is apparent from the data in Tables 1, 2, and 3 that there are wide variations in the abundances of radiohalos in those granitic rocks. Furthermore, *Gentry* [1968] estimated there were as many as 20,000–30,000 ^{218}Po and ^{210}Po radiohalos per cm^3 in biotite in a Norwegian granitic pegmatite, while he [*Gentry*, 1999] estimated there are more than one billion U and Po radiohalos in fluorite in a German vein. And there doesn't seem to be a consistent pattern in the abundances of the three types of Po radiohalos.

In Appendix B an attempt is made to explain these abundance variations in terms of three key factors within the hydrothermal transport model for Po radiohalo formation. The first factor is the volume of hydrothermal fluid flow, the second is the quantity of available U-decay products, and the third is the availability of sufficient numbers of sites chemically conducive to Po isotope deposition. Related to the second factor are the varying abundances of zircon grains in the granitic rocks; the more zircon grains there are, the more U-decay products are available to form more Po radiohalos. Several additional factors might explain the different abundances of the Po radiohalos. These include the distances between the zircon grains and the Po radiocenters; the greater the distance the more likely only ^{210}Po radiohalos will form. Also, there is the overall state of crystallinity of the zircon grains and the diffusion of the ^{222}Rn and Po isotopes out of them. If ^{222}Rn diffuses out into the hydrothermal fluids, ^{218}Po radiohalos may form. However, because of the short half-lives of ^{218}Po and ^{214}Po, if only Po isotopes diffuse out of the zircons, only ^{210}Po radiohalos will probably form.

6.7 The Heat Problem

Radioisotope decay generates heat, so accelerated radioisotope decay would have generated enormous quantities of heat in a very short time. Furthermore, if granitic magmas cooled in 6–10 days during the Flood, there is also the heat they released that needed to be removed along with the heat generated by the simultaneous accelerated radioisotope decay. This problem is discussed further in Appendix C. Convective flows of hydrothermal fluids might be capable of moving and dissipating heat from granitic plutons, but an additional, as yet unknown mechanism would have been needed to remove the heat generated by the accelerated radioisotope decay.

6.8 Other Applications and Their Implications

Because there are other sources of hydrothermal fluids apart from cooling granitic magmas, *Snelling and Armitage* [2003] predicted that there may be other geological contexts in which hydrothermal fluids may have transported available U-decay products to generate Po radiohalos. Thus in this study the search for Po radiohalos was extended to metamorphic rocks, and plentiful Po radiohalos were found (Table 4, p. 188). These results and their implications are discussed fully in Appendix D. The hydrothermal fluids responsible for the Po radiohalos confirm the model that regional metamorphic complexes could have been produced by hydrothermal fluid transformation of the minerals in deeply-buried sedimentary rocks. This sets a rapid timescale of only days on both the formation and cooling of metamorphic complexes.

The higher abundance of Po radiohalos in the Land's End Granite of Cornwall, England (Table 2 and Figure 6) was concluded to be due to that granite hosting hydrothermal ore lodes, including those containing U (Appendix D). Thus Po radiohalos associated with deposition of metallic ores by hydrothermal fluids in lodes hosted by granitic and metamorphic rocks could imply their rapid deposition and formation. Additionally, Po radiohalos could therefore provide an exploration tool for the discovery of new metallic ore lodes in prospective host rocks.

7. Conclusions

The evidence from the discovery of the three types of Po radiohalos in the biotites within granitic plutons that can be demonstrated to have formed during the Flood year falsifies the hypothesis for the formation of these Po radiohalos and their host granitic rocks during the Creation week. Furthermore, the presence of dark, mature (fully-formed) ^{238}U and ^{232}Th radiohalos in the same biotites in these same granitic rocks may be interpreted as physical evidence for at least 100 million years worth (at today's rates) of radioactive decay occurring during those parts of the Flood year represented by these granitic rocks. Accordingly, conventional radioisotope dating of rocks based on the assumption of the constancy of decay rates is grossly in error.

The hydrothermal fluid transport model for the secondary formation of the Po radiohalos as proposed by *Snelling and Armitage* [2003] is overwhelmingly confirmed by the evidence gathered in this study from more than fifty granitic plutons. Because the zircon inclusions in the biotite grains contain large amounts of U, ^{238}U decay products readily diffuse out of the zircon crystal lattices. Radon-222 and Po isotopes released from the zircon inclusions are carried by the hydrothermal fluids flowing along the cleavage planes of the biotite grains. These isotopes are carried only short distances (an average of 1 mm) to be deposited at sites where the chemical environment was suitable for concentration of the Po isotopes before they α-decayed. The radiocenters thus formed generated the Po radiohalos. However, due to the annealing temperature of α-tracks being 150°C, even though the transport of these isotopes in the hydrothermal fluids would have been occurring above that temperature, the radiohalos could only form once cooling had reached that temperature. Thus the short half-lives of ^{218}Po and ^{214}Po require the hydrothermal fluid transport and chemical concentration time frames to have been extremely short, less than ten half-lives of these Po isotopes, and calculated to be on the order of hours to just a few days for complete radiohalo formation. Which Po radiohalos form and the abundances of them were determined by the supply of ^{222}Rn and Po isotopes to the hydrothermal fluids (dependent on the U concentrations in the zircons and the diffusion rates), the volume of hydrothermal fluid flow, the distances from the zircon sources to the radiocenters, and the numbers of Po radiocenters that developed (dependent on the metal and other ions available, the numbers of lattice defect sites, and the locally conducive chemical environment). The implication that the short-lived ^{222}Rn and Po isotopes must survive in the cooling granitic magma until the temperature drops below the α-track annealing temperature of 150°C for the Po radiohalos to then form means that the timescale for the cooling of granitic plutons was extremely short, calculated at between six and ten days. And it should be noted that this timescale is constrained by the half-lives of these isotopes, and not by the assumption that these granites formed during the Flood year.

It is also concluded that this hydrothermal fluid transport model for the secondary formation of Po radiohalos also applies to Precambrian (pre-Flood) granitic rocks, whereas in Tertiary (post-Flood?) granitic rocks there has generally been insufficient nuclear decay for enough α-tracks to register as radiohalos. However, because of the annealing temperature of α-tracks being so low at 150°C, even the radiohalos presently observed in the Precambrian granitic rocks had to have formed below that temperature. Thus it is unlikely that the presently observed radiohalos in these rocks were generated at the time when these pre-Flood rocks formed, even if some of them represent Creation week rocks. The heat generated by the accelerated nuclear decay during the Flood, and the catastrophic tectonic and geological processes during the Flood that were driven by heat, might have raised the temperatures in these Precambrian granitic rocks above 150°C, and thus annealed all previous radiohalos. Certainly heat from accelerated radioactive decay would have annealed all previous radiohalos. Connate fluids and groundwaters in granitic and other rocks heated to become hydrothermal fluids would have circulated through pre-Flood granitic rocks and transported ^{222}Rn and Po isotopes from zircons to replenish the Po radiocenters down flow along biotite cleavage planes to generate new Po radiohalos. Thus the thermal annealing temperature of α-tracks at 150°C falsifies the hypothesis that the Po radiohalos we observe in Precambrian granitic rocks were generated by Po created at the same time as those granitic rocks were.

The accelerated nuclear decay, that may be presumed on the basis of concurrent formation of the ^{238}U and Po radiohalos, would have generated enormous quantities of heat. On the basis of present parameters this heat may be estimated to have been sufficient to vaporize the rocks completely. The fact that the zircon inclusions and the biotites with their contained U and Po radiohalos did not vaporize is evidence that the supposed heat generated did not cause a perceived problem. While the convective flows of hydrothermal fluids were capable of moving and dissipating heat from granitic plutons, that mechanism alone would not seem capable of removing the calculated enormous quantities of heat over the brief timescale required to avoid vaporization of granitic rocks due to the accelerated nuclear decay in them. Another mechanism needs to be explored, such as the volume cooling effect of a sudden expansion of the fabric of space.

The discovery of plentiful Po radiohalos in metamorphic rocks extends the application of the hydrothermal fluid transport model for Po radiohalo formation to these rocks, with powerful and far-reaching implications. The required hydrothermal fluid flows dictated by the formation of the Po radiohalos could confirm the model that regional metamorphic complexes were produced by hydrothermal fluid transformation of the minerals in deeply-buried sedimentary rocks. This model would set a rapid timescale on the formation and cooling of regional metamorphic complexes. Only a few days would be required for the temperatures to drop to 150°C and the Po radiohalos then formed. It is also evident that Po radiohalos could be associated with deposition of metallic ores by hydrothermal fluids in lodes hosted by, and associated with, granitic and metamorphic rocks. If preliminary observations of Po radiohalos in association with such hydrothermal ore deposits are confirmed, there is implication for their rapid deposition and formation. Polonium radiohalos can also provide an exploration tool for the discovery of new metallic ore lodes in prospective host rocks. Rather than falsification of the Creation hypothesis for the Po radiohalos in granitic rocks being a disappointment, the Po radiohalos provide powerful evidence for many rapid geological processes consistent with both the year-long catastrophic global Biblical Flood, and a young earth.

8. Further Work

While this study has produced abundant evidence of the widespread occurrence of Po radiohalos in granitic rocks throughout the geologic record, consistent with, and confirming, the hydrothermal fluid transport model for the secondary formation of the Po radiohalos, much further work needs to be done. Many more Precambrian granitic plutons need to be sampled to fill gaps in the coverage of the Precambrian geologic record. The Po radiohalos evidence thus accumulated may help in our understanding of the pre-Flood geologic record, perhaps even helping to define where the Creation week ends in that record. Further sampling of Tertiary granitic plutons would be advisable so as to confirm the general absence of radiohalos in such rocks as due to insufficient nuclear decay having occurred in them. Most importantly, it is desirable that some detailed case studies be undertaken on a moderate number of granitic plutons, involving numerous samples from each pluton so as to increase our understanding of the distribution and abundance of the different radiohalo types. This would particularly include revisiting some of the rocks in which Gentry and others found huge numbers of Po radiohalos. There should be sampling not only of granitic rocks, but also of associated pegmatites and veins. It would be predicted that there could be a higher frequency of Po radiohalos in such pegmatites and veins which form from the late stages of crystallizing granitic magmas (see Appendix B.2). Our understanding of radiohalos is still in its infancy.

With such potential further implications in mind, it is extremely important that the radiohalo studies be extended to metamorphic rocks of all different types, including not only regional metamorphic complexes, but also contact metamorphic rocks where hydrothermal fluid flows have contributed to the transformation of the host rocks in contact with the cooling granitic plutons. Such studies should involve careful sampling of selected regional metamorphic complexes and the metamorphic zones within them to ascertain the distribution and abundances of the Po radiohalos, and also U and Th radiohalos. Such studies could elucidate the hydrothermal fluid flow paths and thus confirm the role of hydrothermal fluids in the formation of the regional metamorphic complexes by the transformation of the original minerals in the precursor sedimentary rocks, as well as confirming the extremely short timescale for the formation of the metamorphic complexes and their cooling.

Polonium radiohalo studies should be extended to the rocks hosting metallic ores that have been deposited by hydrothermal fluid flows which also altered the host rocks. If the preliminary evidence of Po radiohalos being associated with hydrothermal ore veins and lodes is confirmed, then the formation of the Po radiohalos would likewise constrain the deposition of these ore veins and lodes to the rapid timescale for the hydrothermal fluid flows responsible. Such investigations should include some of the hydrothermal ore veins where abundant Po radiohalos were previously documented by Gentry. Furthermore, appropriate studies need to be undertaken to confirm the possibility of Po radiohalos being an exploration tool for the discovery of hydrothermal ore deposits in new districts, and where such ore deposits are so deeply buried that they may not be detected by other exploration methods. Such confirmation of Po radiohalos as an exploration tool would bring them to the attention of the conventional geological community, as well as elaborate their far-reaching implications for the rapid timescale of many geological processes that are usually regarded as taking millions of years.

Acknowledgments

Full acknowledgment is given to the groundbreaking pioneer work on Po radiohalos by Robert Gentry. The training and counsel he provided on radiohalos enabled this research project to be accomplished. Time was spent with Bob in the field, and he also gave personal instruction on the technique of mounting biotite flakes onto microscope slides. It is disappointing that the outcome of this research did not corroborate Bob's hypothesis, but the Po radiohalos still remain profound objective evidence for the rapid formation of granitic rocks, and also probably metamorphic rocks and hydrothermal ore deposits, consistent with a created young earth and the Biblical Flood. In disagreeing with Bob, however, it is important that his essential pioneering research, that was foundational to the research reported here, be recognized and emphasized.

Many people contributed to this research effort, particularly in the provision of the many samples of granitic rocks, either independently or in assisting in the necessary fieldwork. These people include, in alphabetical order, Steve Austin, John Baumgardner, Danny Faulkner, Carl Froede, Paul Garner, Chris Henschke, William (Bill) Hoesch, Peter Klevberg, Mike Oard, Vesa Palonen, Darry Stansbury, Tom Vail, Larry Vardiman, Sandy Waresak, and Kurt Wise. Without the help of these people there would not have been the large number of granitic rock samples that this study reports.

The help of Mark Armitage in the crucial work of preparing microscope slides and then scanning them for radiohalos must be emphasized and gratefully acknowledged. Mark was responsible for processing most of the U.S. and Scandinavian rock samples, while the author was responsible for the processing of all Australian and British samples. Nevertheless, the responsibility for all the results and the interpretation of them rests solely with the author. This research would not have been possible without the gifts of the donors to the RATE project. Those gifts are acknowledged and the donors thanked. The support and helpful advice of the other members of the RATE group are also acknowledged and appreciated.

Appendix A: The Po Radiohalo Formation Model

A.1 A Detailed Description of the Model

Snelling and Armitage [2003] presented a logical argument for the secondary formation of Po radiohalos by transport of ^{222}Rn and Po isotopes in the hydrothermal fluids released by the crystallizing and cooling granitic magmas below 150°C, the thermal annealing temperature of radiohalos in biotite [*Laney and Laughlin*, 1981; *Armitage and Back*, 1994]. This model is shown schematically in Figure 7, from *Snelling et al*. [2003]. The absolutely critical observation on which this model is based is that ^{238}U and Po (most often ^{210}Po) radiohalos are consistently found in the same biotite flakes (Figures 4i-l and 7a). Whereas the ^{238}U radiohalos have tiny zircon inclusions as their radiocenters, almost all the Po radiohalos in these granites have no visible central inclusions as their radiocenters, just tiny empty "holes" or what looks like "bubbles." Because the biotite flakes have been pulled apart along their cleavage planes to be mounted for microscope examination and identification of the radiohalos in them, this implies that when the ^{238}U and Po radiohalos are observed in the same biotite flakes under the microscope, the radiocenters of these radiohalos are all sitting on the same cleavage planes, which of course means that the radiocenters were originally between the same two sheets of the biotite crystal structure (Figure 7a and b). Now because the thermal annealing temperature of radiohalos in biotite is 150°C [*Laney and Laughlin*, 1981; *Armitage and Back*, 1994), this implies that both the ^{238}U and Po radiohalos together in these biotite flakes could only have formed concurrently below that temperature since the last heating of the biotite above 150°C. The formation of both ^{238}U and Po radiohalos would have to have been concurrent, because as the ^{238}U decays and forms its radiohalo, it also supplies the Po required to form the Po radiohalos (see below). However, at the present rate of ^{238}U decay it has been estimated that to develop a fully-formed (mature) ^{238}U radiohalo requires 100 million years worth of such slow radioisotope decay [*Gentry*, 1973, 1974; *Humphreys*, 2000; *Snelling*, 2000]. On the other hand, the Po isotopes that are the daughters produced by ^{238}U decay only have fleeting half-lives, 138 days for ^{210}Po but only 164 microseconds for ^{214}Po. The latter is particularly critical to the situation where ^{214}Po radiohalos are found in the same biotite flakes as ^{238}U radiohalos, implying that they formed concurrently. Thus if 100 million years worth of ^{238}U decay had to have occurred while the Po radiohalos were forming, then this implies the ^{238}U decay had to have been grossly accelerated so that the 100 million years worth of ^{238}U decay could be fitted into the hours and days over which the Po isotopes accumulated in the radiocenters from which the Po radiohalos concurrently formed. This suggests that the Po transport (or infusion) would have been extremely rapid, so modeling this process is necessary. Of course, the obvious implication is that all conventional radioisotope dating of these rocks, based on the assumption of constant decay at today's slow rates, thus would be grossly in error.

Research in experimental igneous petrology has shown that the temperatures required for melting of rocks to form granitic magmas are significantly lowered by increasing water activity up to saturation, and the amount of temperature lowering increases with increasing pressure [*Ebadi and Johannes*, 1991]. A corollary to this is that water solubility in granitic magmas increases with pressure, and therefore depth, so that whereas at 1 kbar pressure (3–4 km depth) the water solubility is 3.7 wt% [*Holtz et al*., 1995], at 30 kbar pressure (100 km depth) the water solubility is approximately 24 wt% [*Huang and Wyllie*, 1975]. Indeed, water is generally recognized as the most important magmatic volatile component, both for its abundance and for its effects on physical and chemical properties of magmas. Furthermore, the role of water in the crystallization of magmas is fundamental. Indeed, plutons with considerable amounts of magmatic water cool much faster than do those which don't. For example, for a granodiorite pluton 10 km wide and emplaced at 7 km depth, the cooling time from liquidus to solidus temperatures decreases almost ten-fold as the water content increases from 0.5 wt% to 4 wt%, other factors remaining constant [*Spera*, 1982]. Following the emplacement of a granitic magma in the upper crust, crystallization occurs by the irreversible loss of heat to the surrounding country rocks [*Candela*, 1992]. As crystallization proceeds, the water dissolved in the magma that isn't incorporated in the minerals crystallizing stays in the residual melt, so the water concentration there increases. When the saturation water concentration is lowered to the actual water concentration in the residual melt, first boiling occurs and water (as superheated steam) is expelled from solution in the melt, which is consequently driven towards higher crystallinities as the temperature continues to fall. Bubbles of water vapor then nucleate and grow, causing second (or resurgent) boiling within the zone of crystallization just underneath the solidus boundary and the already crystallized magma (Figure 8). As the concentration and size of these vapor bubbles increase, vapor saturation is quickly reached, but initially the vapor bubbles are trapped by the immobile crystallized magma crust [*Candela*, 1991]. The vapor pressure thus increases and

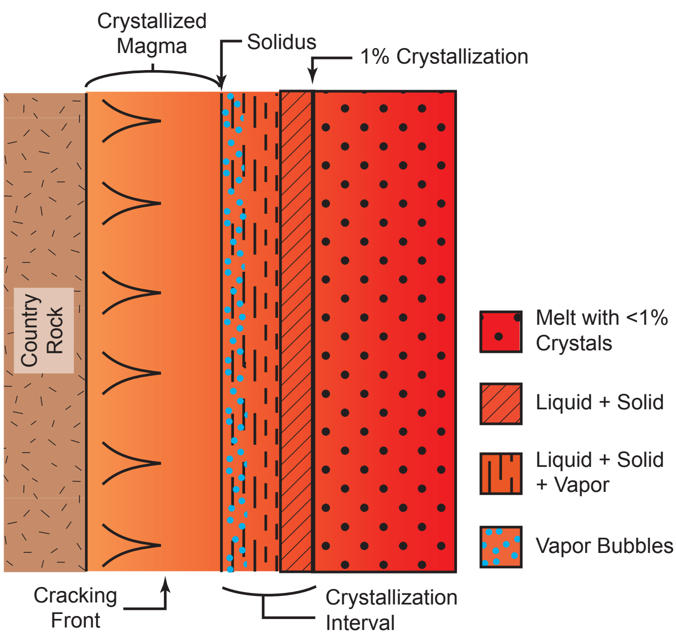


Figure 8. Cross-section of the margin of a magma chamber traversing (from left to right): country rock, cracked pluton, uncracked pluton, solidus, crystallization interval, and bulk melt (after *Candela* [1991]).

the aqueous fluid can then only be removed from the sites of bubble nucleation through the establishment of a three-dimensional critical percolation network, with advection of aqueous fluids through it or by means of fluid flow through a cracking front in the crystallized magma and out into the country rocks (Figure 8). Once such fracturing of the pluton has occurred (and the cracking front will go deeper and deeper into the pluton as the solidus boundary moves progressively inwards towards the core of the magma chamber), not only is magmatic water released from the pluton carrying heat out into the country rocks, but the cooler meteoric water in the country rocks is able to penetrate into the pluton and thus establish hydrothermal circulation. The more water dissolved in the magma, the greater will be the pressure exerted at the magma/rock interface [*Knapp and Norton*, 1981].

Thus by the time the temperature has fallen to 300°C at the core of a granitic pluton the solidus boundary and cracking front have both reached the core of the pluton as well. This means that the magma has totally crystallized into the constituent minerals of the granite. It also means that a fracture network has been established through the total volume of the pluton and out into the surrounding country rocks through which a vigorous flow of hydrothermal fluids has been established. These hydrothermal fluids thus carry heat by convection through this fracture network away from the cooling pluton, ensuring the temperature of the granitic rock mass continues to rapidly fall. The amount of water involved in this hydrothermal fluid convection system is considerable, given that a granitic magma has enough energy due to inertial heat to drive roughly its mass in meteoric fluid circulation [*Norton and Cathles*, 1979; *Cathles*, 1981]. However, there would be even more heat available to drive the circulation of the hydrothermal fluids if accelerated nuclear decay was occurring simultaneously. With such a large volume of hydrothermal fluids percolating through the cooling rock mass, the fluids would also find their way around the grain boundaries of the constituent minerals, and in the case of biotite along its cleavage planes (Figure 7b). Indeed, the heat-driven hydrothermal fluids would force their way along cleavage planes, opening them up to the fluid flow. Between some of the cleavage planes in some of the biotite flakes within the granitic rock are included zircon crystals, and these contain large quantities of trace U, sometimes as much as several hundred ppm. Because of the accelerated nuclear decay occurring concurrently with crystallization of the granitic pluton, the zircons would also contain relatively large concentrations of the ^{238}U decay daughter isotopes, including ^{222}Rn and the three Po isotopes. In fact, it is because ^{238}U decay in the zircons is required as the source of the Po isotopes to produce the Po radiohalos that the ^{238}U and Po radiohalos had to have formed concurrently.

Now Rn is an inert gas, meaning that its atoms have no chemical affinity that would attract them and/or attach them to atoms of other elements, and meaning that its atoms have so much vibrational energy that they neither cohere to form a liquid or link to one another to form a solid. Because of these properties, and because of the heat still in the granite, the ^{222}Rn easily diffuses out of the zircon crystal lattice in spite of the large size of its atoms and dissolves in the hydrothermal fluid flowing along the biotite cleavage planes past the zircon crystal. As it is then carried down flow along the cleavage planes from the zircon crystal the ^{222}Rn eventually α-decays through ^{218}Po, that then subsequently α-decays to ^{214}Po and finally ^{210}Po, while the ^{238}U still in the zircon crystal also α-decays. However, at temperatures above 150°C all α-tracks are annealed [*Laney and Laughlin*, 1981; *Armitage and Back*, 1994], so no radiohalos form and there is no α-track record of the hydrothermal fluids containing the Rn and Po flowing along the cleavage planes (Figure 7c). Similarly, above 150°C α-recoil traces are also annealed. Of course, the hydrothermal fluids would also carry in solution various metals, usually in trace amounts (but sometimes in sufficient quantities to be deposited and concentrated as economic hydrothermal ore deposits). Sulfur is a key component of such ore deposits and granitic rocks, which even when not hosting or associated with hydrothermal sulfide ore deposits contain trace to minor amounts of S. Because the S atoms in granitic rocks are not always found in discrete sulfide minerals it is not unusual for them to be incorporated in the silicate minerals in lattice defects. This could have been accomplished by S atoms being incorporated in mineral lattices at the time those minerals were crystallizing, but it can also result subsequently, such as in biotite, when these late-stage hydrothermal fluids flow along the cleavage planes (Figure 7c).

As the temperature of the granite continues to fall towards 150°C, and ^{222}Rn that has diffused out of the zircon and been included in the hydrothermal fluids flowing past continues to decay to ^{218}Po, the Po isotopes in the hydrothermal fluids would precipitate to form PoS as the fluids flow by the S atoms in the lattice defects, because Po has a geochemical affinity for S [*Bagnall*, 1957] (Figure 7d). The ^{238}U in the zircon also continues to decay and therefore replenish the supply of ^{222}Rn and Po isotopes in the hydrothermal fluids flowing along the cleavage planes in the biotite past the zircon. All α-tracks being produced by the α-decays in the ^{238}U series, whether surrounding the zircon, around the fluid flow paths along the cleavage planes, or around the S atoms where Po isotopes had precipitated, continued to be annealed so there is no preserved record of either those α-decays or the hydrothermal fluid flow along the cleavage planes, except for pervasive chloritization of the biotite. As the Po in the PoS α-decays the S atoms are then available to attract more Po isotopes from the hydrothermal fluids flowing past to reform the PoS radiocenters. Additionally, as the Po eventually decays to Pb, the Pb will also assist in the further concentration of new Po from the passing hydrothermal fluids into the radiocenters, because Pb also has a geochemical affinity for Po (forming PbPo or lead polonide) [*Bagnall*, 1957].

Once the temperature drops to below 150°C, the α-tracks produced by the continued α-decay of the ^{238}U in the zircon and of the Po isotopes in the PoS are no longer annealed, and so the α-tracks produced by α-decay start discoloring the biotite sheets surrounding the zircon crystal and the tiny PoS accumulations (Figure 7e). With the passage of time these processes continue so that more α-decays of both the ^{238}U in the zircon radiocenters and the Po isotopes in the PoS radiocenters produce α-tracks that continue discoloring the surrounding biotite sheets until the resultant ^{238}U and Po radiohalos are fully formed (Figure 7f). Eventually, the hydrothermal fluid flow ceases as the granite cools completely within weeks (see below). Thus if there is no further replenishment of the Po radiohalos centers, there is no further darkening of the Po radiohalos. Nevertheless, Po radiohalos might conceivably form for as long as water continued to diffuse through any mineral that contained U. Within two to three years of Po radiohalo formation commencing U-bearing minerals would be the only potential source of solution-transportable Po. But the problem would then be whether there is sufficient Po available to be dissolved, another reason why visible Po radiohalos would not have formed after the Flood. On the other hand, the ^{238}U in the zircons continues to α-decay so that the resultant ^{238}U radiohalos continue to darken right through until the present time.

It is important to note that both ^{238}U and Po radiohalos (Figure 7) have to form concurrently and are evidenced by halos only when the granite has cooled to below 150°C. The upper limit for the rate at which these processes occur must therefore be governed by the 138 day half-life of ^{210}Po when ^{238}U and ^{210}Po radiohalos are found in the same biotite flakes. Of course, for ^{218}Po and ^{214}Po radiohalos to be generated in the same biotite flakes in which ^{238}U radiohalos around zircon grains also occur, these processes would have to have occurred at very much faster rates, as governed by their very much shorter half-lives. However, because this model for Po radiohalo formation requires ^{238}U decay to have been grossly accelerated by a factor of at least 10^6, it might be expected that the decay of the Po isotopes and their precursors would likewise have been accelerated by a similar factor, thus placing even tighter time strictures on these processes described above. This may not be the case. *Austin* [2005] and *Snelling* [2005] have argued that the discordances between the isochron ages obtained on the same rocks by the different radioisotope systems can only be resolved if the acceleration factor was a function of the decay half-life (and perhaps the atomic weight), such that the longer the half-life of a radioisotope, the more its decay was accelerated. If this were the case, because the half-lives of the Po isotopes and ^{222}Rn are so fleetingly short compared to the half-life of ^{238}U, the decay of the Po isotopes and ^{222}Rn would hardly have been effected by the acceleration of ^{238}U decay. In contrast, those ^{238}U decay products that presently have longer half-lives, such as ^{234}U (248,000 years), ^{230}Th (75,000 years), ^{226}Ra (1662 years), and ^{210}Pb (22 years), would have had their decay accelerated by different factors, but very much lower than that for ^{238}U decay.

A.2 The Source of the ^{238}U Decay Products

There are a few essential components of this Po radiohalo formation model that were dealt with by *Snelling and Armitage* [2003], but which need to be reiterated here. First is the question of the source of the ^{238}U decay products, principally the three Po isotopes. *Snelling and Armitage* [2003] argued that in the three granitic plutons they studied the only common plausible source of ^{238}U decay products was the zircon grains in these granitic rocks that commonly contained tens to hundreds of ppm U. Tiny zircon grains containing large quantities of trace U are also present in all the granitic rocks listed in Tables 1, 2, and 3. These are the U contents of the zircons at the present time, after hundreds of millions of years worth (at today's rates) of ^{238}U decay has occurred to produce the conventional radioisotope ages for these granitic rocks. So this not only implies even greater U contents in these zircons when the granitic rocks formed, but this ^{238}U decay would have produced hundreds of millions of years worth of decay products, including ^{222}Rn and the three Po isotopes. Because the ^{238}U and Po radiohalos had to form concurrently this ^{238}U decay had to have been occurring at a greatly accelerated rate, so even before hydrothermal fluids began transporting these isotopes, large quantities of them would be generated in the zircon grains.

A.3 Hydrothermal Fluid Transport

The radiohalos would only be preserved in biotites after the temperature of the newly-formed granitic plutons falls below 150°C, because above that temperature the α-tracks would have been erased. Such temperatures correspond to the middle of the regime of hydrothermal fluids. Depending on the depth of emplacement during magma intrusion, 150°C is well below the temperature of second boiling and magma degassing (about 370°C depending on the confining pressure), when the water and volatiles held in solution within the magma are released [*Burnham*, 1997; *Giggenbach*, 1997].

Of course, the hydrothermal fluid transport of U-decay products such as ^{226}Ra, ^{222}Rn, and the three Po isotopes would have started as soon as the hydrothermal fluids were generated at above 300°C, so the ^{226}Ra, ^{222}Rn, and ^{218}Po could already have been transported by the hydrothermal fluids some distance before the temperature fell to 150°C without leaving any α-track record of their passage. However, by the time the temperature dropped below the α-track thermal erasure threshold at around 150°C in biotite, only the three Po isotopes can have been incorporated in new radiocenters, as there is no evidence of any other α-emitters in the resultant Po radiohalos [*Gentry*, 1971; *Gentry et al*., 1973]. Thus, it would seem more plausible to postulate that ^{226}Ra and/or ^{222}Rn would have been the isotopes initially transported by the hydrothermal fluids, because their half-lives of 1622 years and 3.8 days respectively (the latter especially not appreciably effected by the acceleration of ^{238}U decay) would have allowed more time and thus greater distances for the transport process than the 3.1 minute half-life of ^{218}Po (which was initially regarded as a major obstacle to any secondary transport process). Of course, the transport process could also have started with ^{210}Po because of its 138 day half-life, but only ^{210}Po radiohalos would have resulted.

Brown [1997] favored ^{226}Ra to allow the most time for transport over the required distances, yet he calculated that given a constant supply of ^{226}Ra in a hydrothermal fluid the equilibrium concentrations in the fluid of all three Po isotopes would require, beginning at the zero level, about 100 years. *Snelling and Armitage* [2003] therefore discounted ^{226}Ra transport in the hydrothermal fluids as the primary isotope responsible for supply of the Po isotopes to the Po radiohalo centers, because that time frame is longer than the time frame allowable for the cooling of the granitic rocks from the temperatures at which the magmas were intruded. Indeed, because granitic magmas were generated by the partial melting of fossiliferous Flood-deposited sediments, and those magmas then intruded into overlying fossiliferous sediments deposited later in the Flood, to then cool in time for erosion at the end of the Flood to expose the resultant plutons at the earth's surface today, the time frame for cooling of the granitic rocks and the hydrothermal fluid transport of the U-decay products has to have been very much less than a year. Additionally, ^{222}Rn is favored over ^{226}Ra as the start of the hydrothermal fluid transport process because there are two α-decay steps from ^{226}Ra to ^{218}Po, but only one α-decay step from ^{222}Rn to ^{218}Po. Due to α-track annealing there is no observable α-track record along the biotite cleavage planes where the hydrothermal fluids have flowed, so ^{222}Rn is preferred because there would be fewer α-tracks to be annealed. In any case, as an inert gas ^{222}Rn would have more readily diffused out of the zircon crystal lattice than ^{226}Ra, which because of its ionic charge and chemical bonding is more likely to be slower at diffusing out of the zircon crystal lattice. Radon-222 is readily soluble in water and has a diffusion coefficient of 0.985 cm^2 per day (1.14×10^{-5} cm^2 sec^{-1}) at a water temperature of only 18°C [*Bagnall*, 1957], so its diffusion rate would be much faster in water at 100–200°C. Furthermore, because the source of the ^{222}Rn is the zircon crystals within the same biotite flakes as the resultant Po radiohalos, the transport distances are in the micron (μm) to millimeters (mm) range. Therefore, these distances could easily have been accomplished within the flowing hydrothermal fluids along the biotite cleavage planes within the 3.8 day half-life of ^{222}Rn.

However, *Gentry* [1989, 1998] has maintained that the Po radiohalos do not occur along cracks or conduits in biotite, pointing to photographic evidence [*Gentry*, 1967, 1968, 1971, 1973, 1974, 1984, 1988]. This assertion is emphatically incorrect. Biotite flakes are peeled apart along their cleavage planes when mounting them for observation and photography, which is why cracks or defects are not usually seen. Thus radiohalos in biotites are always on cleavage planes, which are "ready made" cracks in the biotite's crystal structure that provide conduits for the flow of fluids. Nevertheless, Po radiohalos have been observed along fractures in biotite flakes, such as the group of ^{218}Po radiohalos and the ^{214}Po radiohalo in Figure 9. Even *Gentry* [1996] has conceded that secondary ^{210}Po radiohalos do occur in biotites along cracks where there are also discoloration lines and bands that follow the cracks, evidence of the passage of fluids with α-particle radioactivity in solution. Similar observations were first made by *Henderson and Sparks* [1939] who published photomicrographs illustrating this phenomenon. *Meier and Hecker* [1976] recorded such U and ^{210}Po bands along conduits in

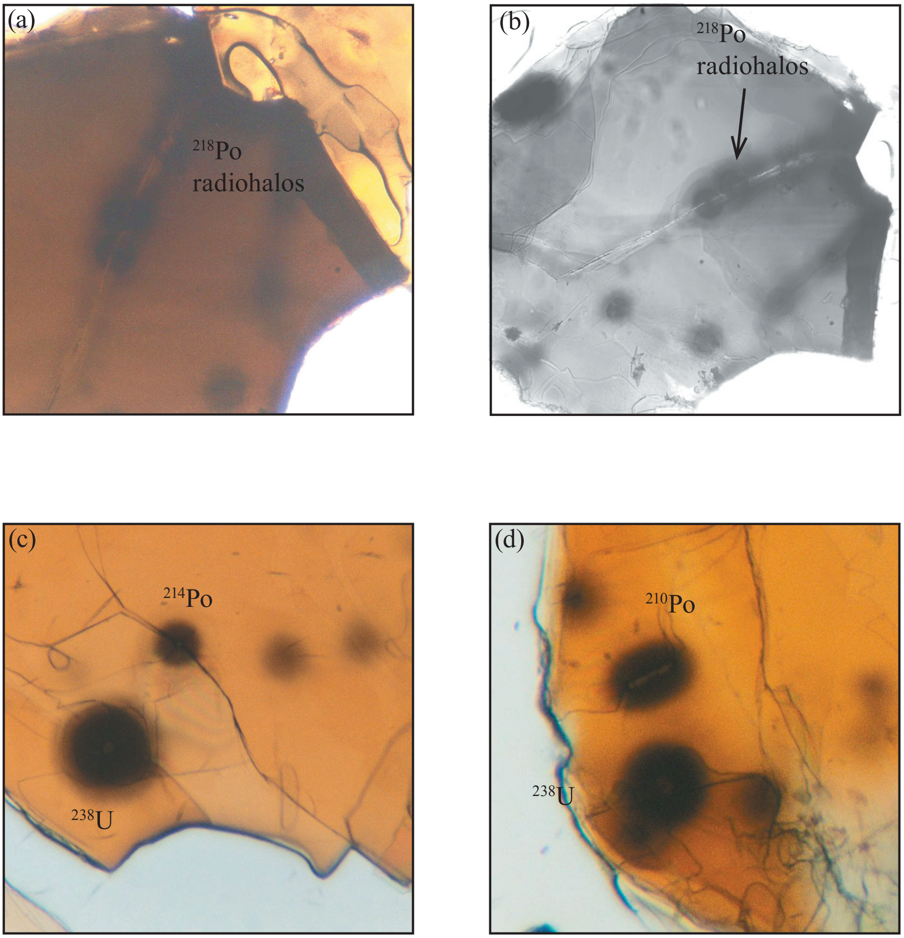


Figure 9. ^{218}Po radiohalos centered along a crack in a biotite flake along which hydrothermal fluids containing ^{218}Po have flowed: (a) color image, (b) black and white image (Stanthorpe Adamellite, the diameter of the radiohalos is ~68 μm). A ^{214}Po radiohalo centered on an apparent crack in a biotite flake (c), and continuous overlapping overexposed ^{210}Po radiohalos (d) in which the radiocenters are connected along a line, suggesting a linear fluid inclusion contained ^{210}Po (Land's End Granite, radiohalo diameters ~68 μm and ~39 μm respectively). Both (c) and (d) also show adjacent overexposed ^{238}U radiohalos (diameters ~70 μm).

biotite. Furthermore, *Gentry et al.* [1974] also noted that single halos are observed around discrete inclusions lodged in conduits or cleavage cracks, while vein halos formed from a continuous distribution of radioactivity apparently deposited from hydrothermal solutions along conduits.

A.4 Supply of Sufficient Polonium

Gentry [1974] calculated that the radiocenters of very dark ^{218}Po radiohalos may have needed as many as 5×10^9 atoms of ^{218}Po each to have produced the ^{218}Po radiohalos, so would hydrothermal fluid transport of ^{222}Rn be able to supply enough ^{218}Po atoms to the radiocenters within the required time frame? Of course, similar numbers of ^{214}Po and ^{210}Po atoms would thus have been needed in radiocenters to produce the respective radiohalos. In Gentry's fiat Creation model all 5×10^9 atoms of Po (a concentration of more than 50%) need to be in the radiocenters all at once at the time of their formation in order to subsequently produce the Po radiohalos. However, *Snelling and Armitage* [2003] have argued that because some granites containing Po radiohalos can be demonstrated to have formed during the Flood event neither the granites nor the Po are primordial (created by fiat). This conclusion is supported by the very much larger dataset here in Table 2. On the other hand, *Snelling and Armitage* [2003] argued that the ^{222}Rn hydrothermal fluid transport model does not require all 5×10^9 atoms of Po to be delivered to each radiocenter at the same time, because the fluid flow can progressively supply this quantity over a period of days, the Po in the fluids replacing the Po in each radiocenter after it α-decays. All that is required is a steady hydrothermal fluid flow with a constant supply of ^{222}Rn and Po isotopes, together with favorable conditions at the deposition sites that became the radiocenters.

Furthermore, given that 1 g of ^{238}U contains 2.53×10^{21} atoms and in radioactive equilibrium with them at present decay rates are 5.8×10^9 atoms of ^{222}Rn and 3.22×10^6 atoms of ^{218}Po [*Friedlander et al.*, 1964], even when the zircon grains in the biotites of the granitic rocks only have U concentrations of hundreds of ppm, the relative numbers of

^{222}Rn and ^{218}Po atoms would still be sufficient to progressively deliver the needed concentrations of Po isotopes to the new radiocenters. This would be especially so if during the transport process there was accelerated nuclear decay of ^{238}U, which would supply even greater numbers of atoms of the decay products than at the present decay rate. Additionally, for every 2.53×10^{21} ^{238}U atoms there are 2.12×10^{11} ^{210}Po atoms, so that given the longer half-life of ^{210}Po (138 days compared with the 3.8 days of ^{222}Rn), its probably similar diffusion rate to ^{222}Rn [*Frey et al.*, 1981; *Snelling and Armitage*, 2003], and the fact that Po is also readily transported in hydrothermal fluids as halide and sulfate complexes [*Bagnall*, 1957], concurrent hydrothermal fluid transport of ^{210}Po would likely have occurred. This would in part explain the consistently high numbers of observed ^{210}Po radiohalos in the granitic rocks listed in Table 2 compared with the numbers of other Po radiohalos. Such hydrothermal fluid transport of ^{210}Po has already been documented, being measured over distances of up to several kilometers and transit times of 20–30 days [*Hussain et al.*, 1995; *Snelling*, 2000].

A.5 Transport Timescale

It is difficult to determine the precise timescale for the hydrothermal fluid transport of ^{222}Rn and for the establishment of the new radiocenters for subsequent Po radiohalo development. The rarity of ^{218}Po radiohalos in the biotites of most of these granitic rocks would seem to be significant. Transport was evidently slow enough for most ^{218}Po atoms to decay in transit before reaching the sites where ^{210}Po was deposited to generate ^{210}Po radiohalos. The extremely short half-life of ^{214}Po (164 microseconds) gives it a lower probability of surviving transport than ^{210}Po has. In most of these granitic rocks ^{210}Po radiohalos outnumber all other radiohalo types. Even though there is not a consistent abundance pattern, the quantities of the different Po radiohalos must be related to the transport mode, distance, and time. This observation alone lends support to the secondary transport model of separation of the Po isotopes from their parent ^{238}U in the formation of the three discrete types of Po radiohalos.

Given the measured diffusion coefficient of ^{222}Rn of 0.985 cm^2 per day in water at 18°C [*Bagnall*, 1957] and its 3.8 day half-life, it may be possible to quantify, or set limits on, the timescale for the hydrothermal transport of ^{222}Rn and the generation of Po radiohalos. It is reasonable to assume that the diffusion coefficient of ^{222}Rn would be much greater in water temperatures of 100–200°C (compared with 18°C), possibly even an order of magnitude higher (as determined by other diffusion measurements, such as for He [*Humphreys et al.*, 2003, 2004; *Humphreys*, 2005]). But this diffusion coefficient was measured in a stationary body of water, whereas the hydrothermal fluids in these cooling granitic rocks have flowed along fractures, around grain boundaries, and along the cleavage planes in biotite grains. Indeed, the fluid flow would likely be a greater factor in Rn transport than diffusion in the water. Even though hydrothermal fluid transport of ^{210}Po has been measured over distances of up to several kilometers over transit times of 20–30 days [*Hussain et al.*, 1995; *Snelling*, 2000], in that example the hydrothermal fluids were flowing through major fractures in basalts on the ocean floor. In contrast, the hydrothermal fluid transport being modeled in this instance requires flow into and along the cleavage planes of biotite grains, which are very much "tighter" than fractures, or even grain boundaries, and thus much more resistant to fluid penetration. Therefore, a more appropriate, conservative estimate of the diffusion of ^{222}Rn in hydrothermal fluids at 100–200°C might be 20 cm^2 per day, which would equate to a linear diffusion rate of the order of 5–6 cm per day. If the average distance of separation is 1 mm between the zircon source of the ^{222}Rn and Po isotopes and the site of deposition of the Po isotopes in a radiocenter to form a Po radiohalo, then at that diffusion rate a ^{222}Rn atom would travel 1 mm in approximately 30 minutes. Because the diffusion coefficient of Po appears to be similar to that of ^{222}Rn, the Po isotopes would also be transported in the flowing hydrothermal fluids at those temperatures over a distance of 1 mm in approximately 30 minutes.

So even though the half-lives of ^{218}Po and ^{214}Po are 3.1 minutes and 164 microseconds respectively, the ^{222}Rn atoms that α-decay just as they arrive near the radiocenter deposition site will contribute to either a ^{218}Po radiohalo or a ^{214}Po radiohalo. Because ^{222}Rn has a half-life of 3.8 days, each ^{222}Rn atom has more than three days to diffuse out of the crystal lattice of the zircon before being picked up by the hydrothermal fluids flowing past. Atoms of ^{218}Po and/or ^{214}Po that were at the surface of the zircon grain could dissolve into the hydrothermal fluids flowing past, so that by the time those atoms reached and were deposited in the radiocenter 1 mm distance away they would have α-decayed to ^{210}Po and a ^{210}Po radiohalo would therefore be generated. This would explain the much larger numbers of ^{210}Po radiohalos in the majority of these granitic rocks, particularly if most of the Po atoms were the ^{210}Po isotope by the time they diffused out of the zircon crystal lattice and were transported by the flowing hydrothermal fluids. Of course, these estimates are conservative, so this transport timescale could be much shorter, perhaps short enough for ^{218}Po atoms to be carried from the surface of the zircon crystal to the radiocenter before α-decaying and thus generate a ^{218}Po radiohalo.

The next issue is the question as to whether, and over what timescale, this hydrothermal fluid transport rate would deliver the 5×10^9 atoms of Po to the radiocenter in time for it to generate the relevant Po radiohalo. If it is postulated that the flowing hydrothermal fluids deliver Po atoms to the new radiocenter at a rate of 10^6 atoms per second, the 5×10^9 atoms of Po required to produce a very dark Po radiohalo would be delivered in approximately three hours. Five $\times 10^9$ atoms represents a concentration of more than 50%, so 10^6 atoms of Po in the hydrothermal fluids coming in contact with the radiocenter each second represents a concentration of just over 100 ppm Po, which is not excessive given the ease with which Po dissolves in hydrothermal fluids as halide and sulfate complexes, and the concentrations of hundreds of ppm of the parent ^{238}U in the zircon crystals. Polonium-218 or ^{214}Po atoms delivered to the new radiocenter would α-decay within minutes or fractions of a second, respectively. As Po atoms are progressively delivered to the radiocenter over three hours, the ^{218}Po or ^{214}Po radiohalo would be fully formed approximately within the same timescale. Of course, the complete timescale for formation of these Po radiohalos would also include the transport of atoms from the surface of the zircon crystal to the radiocenter. Transport at a rate of 1 mm every thirty minutes would allow delivery of the required concentration of atoms to the radiocenter within that three hours.

However, an equally important factor would be the timescale for the diffusion of ^{222}Rn and Po atoms from inside the crystal lattice of the zircon grain to the grain surface. The zircon grains in the centers of ^{238}U radiohalos are typically 1–10 µm wide, so the distances the ^{222}Rn and Po atoms have to diffuse are very tiny. Larger zircon grains (up to 150 µm long) are often also present in these granitic rocks [*Humphreys*, 2005]. Their relatively larger surface areas (compared with those of the 1–10 µm wide zircons in the ^{238}U radiohalo centers) would also provide an abundant ready supply of ^{222}Rn and Po atoms that also only had to diffuse very tiny distances (< 10µm) out of those zircon crystals. Furthermore, the diffusion of ^{222}Rn and Po atoms out of the zircon grains would have commenced in the hot crystallized granitic rock at temperatures as high as 400°C, so many of these atoms would begin reaching the surfaces of the zircon grains in the time taken for the granitic rock to cool from 400°C to below 150°C. The higher temperatures also cause higher diffusion rates.

These considerations would suggest that ^{222}Rn and even Po atoms would be available at the surface of the zircon grains as soon as hydrothermal fluids were available to begin transporting them, which would have been at temperatures as high as 300°C. On the other hand, this could also put constraints on the timescale for the temperature of the cooling granitic rock to fall from 400°C to 150°C, given the 3.8 day half-life of ^{222}Rn. Indeed, even with a continuous supply of ^{222}Rn from accelerated ^{238}U decay, many of the ^{222}Rn atoms would have already α-decayed to the Po isotopes (principally ^{210}Po) if the timescale for this cooling temperature interval was too long, equal to or greater than 3.8 days. Given that there is only a limited, finite amount of ^{238}U in the zircon grains and thus potential ^{238}U decay products, to maximize the likelihood of Po radiohalo formation it would be optimal for much of the ^{222}Rn to not have decayed to the Po isotopes while still in the zircon grains and in the hydrothermal fluids as the temperatures fall from 400°C to 150°C.

Thus these calculations, which are somewhat conservative, would suggest that the existence of ^{218}Po and ^{214}Po radiohalos in these granitic rocks might require the granitic rocks to cool from 400°C to 150°C in three days or less, and these Po radiohalos would then be generated within three hours subsequent to the temperature falling to 150°C. Transport distances between the zircon grains and the new radiocenters very much greater than 1 mm would favor the generation of only ^{210}Po radiohalos, because of the longer half-life (138 days) of that isotope. This is clearly consistent with the greater number of ^{210}Po radiohalos in these granitic rocks. Another implication of these calculations is that if these granitic rocks cooled from a temperature of 400°C to 150°C in less than three days, and even if there were an exponential decline in the temperature, the time frame for further cooling from 150°C to the ambient temperatures at the intrusion depths of 2–4 km (40–80°C depending on the geothermal gradient) would have to have been less than a further three to seven days. This then would be the time frame for the window in which hydrothermal fluid flow would be occurring below the annealing temperature of α-tracks in biotite to produce all the Po radiohalos, because once hydrothermal fluid flow ceased no further transport of Po isotopes to the radiohalo deposition sites would be occurring.

Furthermore, there are two other implications of these timescale calculations. First, they provide an absolute and objective timescale for the cooling of granitic plutons independent of the assumption that these granitic rocks formed during the Flood event. Because the existence of the ^{218}Po and ^{214}Po radiohalos can only be explained in a timescale for their generation during cooling of these granitic plutons from above 400°C to below 150°C, whereupon the α-tracks generated by Po isotope decay are retained in the biotite crystals to register as radiohalos, then the calculated timescale for generation of these Po radiohalos automatically becomes a measure of the timescale for the cooling of granitic plutons. And that timescale for cooling of granitic plutons from 400°C to 150°C to near-surface crustal temperatures has been calculated here conservatively as a total of only six to ten days! The second implication directly follows. This extremely short timescale for cooling of the granitic plutons and therefore the concurrent flow of hydrothermal fluids automatically precludes ^{226}Ra, with its half-life of 1622 years, as the precursor isotope to the Po isotopes that is transported in the hydrothermal fluid flows. Put simply, if the time window for hydrothermal fluid flow in the cooling granitic plutons is only six to ten days, there is insufficient time for α-decay of enough ^{226}Ra, to even begin generating any Po radiohalos.

For comparison with all the calculations here, it is instructive to review the detailed analysis of the fluid transport of these radionuclides by *Feather* [1978], of the Department of Physics at the University of Edinburgh. In summary, Feather found that if a hydrothermal fluid is assumed to take up ^{226}Ra preferentially from a U source, and if two types of inclusion are present in the biotite, one type providing deposition centers for the Po isotopes, and other centers for deposition of Bi (or Pb) isotopes; then ideal situations may be identified in which Po radiohalos of each of the three types might develop. Basically, he calculated that the discriminating factor is the time of transit of the hydrothermal fluid from the U source to the deposition sites. Transit times ranging upwards from about 20 days favor the development of ^{210}Po radiohalos, transit times of less than five days are required for the development of ^{218}Po radiohalos, and even shorter transit times are necessary (five hours or less) if ^{214}Po radiohalos are to be formed. To this extent Feather was satisfied that the fluid transport hypothesis achieves formal success in producing secondary Po radiohalos.

Note that Feather's transit times are longer because he starts with ^{226}Ra rather than ^{222}Rn, and his model relies only on the flow of the hydrothermal fluids to carry the isotopes over those transit times. On the other hand, in the model calculations here, ^{222}Rn is instead the starting isotope, and atoms of both ^{222}Rn and the Po isotopes also diffuse within the flowing hydrothermal fluids. Thus the transit times are very much shorter. Furthermore, *Feather* [1978] did not take into account either the time constraints the cooling of the granites placed on the overall transit times, or the effect of the limitation of α-track and radiohalo formation to temperatures below 150°C. Therefore it is confidently asserted that the transit times and timescales for Po radiohalo development and granite cooling calculated here are well constrained by all the relevant factors, and thus are very reasonable.

A.6 Establishment of New Radiocenters

There needs to be a mechanism by which the Po isotopes are concentrated at particular (seemingly random) locations to become discrete radiocenters. Most of the hydrothermal fluid transport would be as ^{222}Rn, an inert gas that has no chemical affinity with other species, and no propensity to concentrate by precipitating at discrete locations. Thus, as *Snelling and Armitage* [2003] concluded, it would appear that the radiocenters could only have been formed by the Po atoms resulting from the decay of ^{222}Rn. Polonium behaves geochemically similar to Pb, with an affinity for S, Se, and halides, and even forms polonides with other metals including Pb [*Bagnall*, 1957]. Indeed, *Gentry et al.* [1976b] have demonstrated that where Pb, S, and Se were available in coalified wood, Po transported through the coalified wood by groundwaters became attached to these species, and became concentrated enough in such radiocenters to produce ^{210}Po radiohalos.

Ilton and Veblen [1988] discovered that some biotite grains in granitic rocks that host hydrothermally-produced porphyry Cu ore deposits have inclusions of native Cu 0.002–0.01 μm thick and up to 1.0 μm in diameter in favored lattice planes. They concluded that these tiny Cu inclusions had been deposited from the Cu-bearing hydrothermal fluids that flowed along the cleavage planes within the biotite crystals. *Snelling and Armitage* [2003] therefore concluded that it is thus reasonable to expect that the same hydrothermal fluids that transported Rn and Po isotopes would also have transported metal and other ions [*Giggenbach*, 1997, *Seward and Barnes*, 1997]. Because Po isotopes are readily transported in hydrothermal fluids as halide and sulfate complexes [*Bagnall*, 1957], which are common in hydrothermal fluids [*Giggenbach*, 1997], all that is required for the development of Po radiocenters is for sulfate ions to be reduced at lattice defect sites within the biotite cleavage planes so PoS (polonium sulfide) is precipitated. Similarly, other metals and elements would also be deposited as tiny inclusions along the cleavage planes within the biotites. *Collins* [1992] has correctly noted that the crystal lattice of biotite contains sites where negatively charged halide or hydroxyl ions can be accommodated. Thus *Snelling and Armitage* [2003] concluded that these lattice sites and other imperfections found along cleavage planes in biotites, being relatively large, would provide space for metal and other ions such as Po to enter and take up lattice positions or to be concentrated at particular discrete places along the cleavage planes where the chemical environment was conducive. Indeed, *Collins* [1992] also contended that the Po radiohalos formed as a result of diffusion of ^{222}Rn in "ambient" fluids within the crystallizing granitic rocks.

Another factor in this process is the effect the hydrothermal fluids have directly upon the biotite itself. Invariably, because the hydrothermal fluids contain many dissolved ions such as halides and sulfate they are highly reactive, and thus as they flow along the biotite cleavage planes they interact with the biotite crystal lattice changing its structure by exchange and addition of ions to partly change the biotite into the mineral chlorite. Thus primary evidence that hydrothermal fluids have flowed along the cleavage planes of the biotites in these granitic rocks is the universal observation of the chloritization of all biotite flakes (Figure 10a and c). Equally compelling evidence of the hydrothermal fluid flow along the biotite cleavage planes is the preservation in some of the biotites of the remains of what were fluid-filled inclusions (Figure 10b and d). Fluid inclusions may even have formed radiocenters (Figure 9d), which may explain the bubble-like "holes" and the absence of visible inclusions in almost all Po radiohalos. It is now well established that the chlorite alteration caused by hydrothermal fluids concurrently accompanies the process of deposition of metals and other ions from the hydrothermal fluids, primarily including the precipitation of sulfides [*Reed*, 1997]. Once the center of nucleation is established a sulfide crystal can grow rapidly from the components precipitated and scavenged from the hydrothermal fluids flowing by. *Snelling and Armitage* [2003] concluded that in this way Po was incorporated in discrete radiocenters along the cleavage planes in the biotite flakes where other suitable ions such as S had been concentrated in the lattice sites and crystal

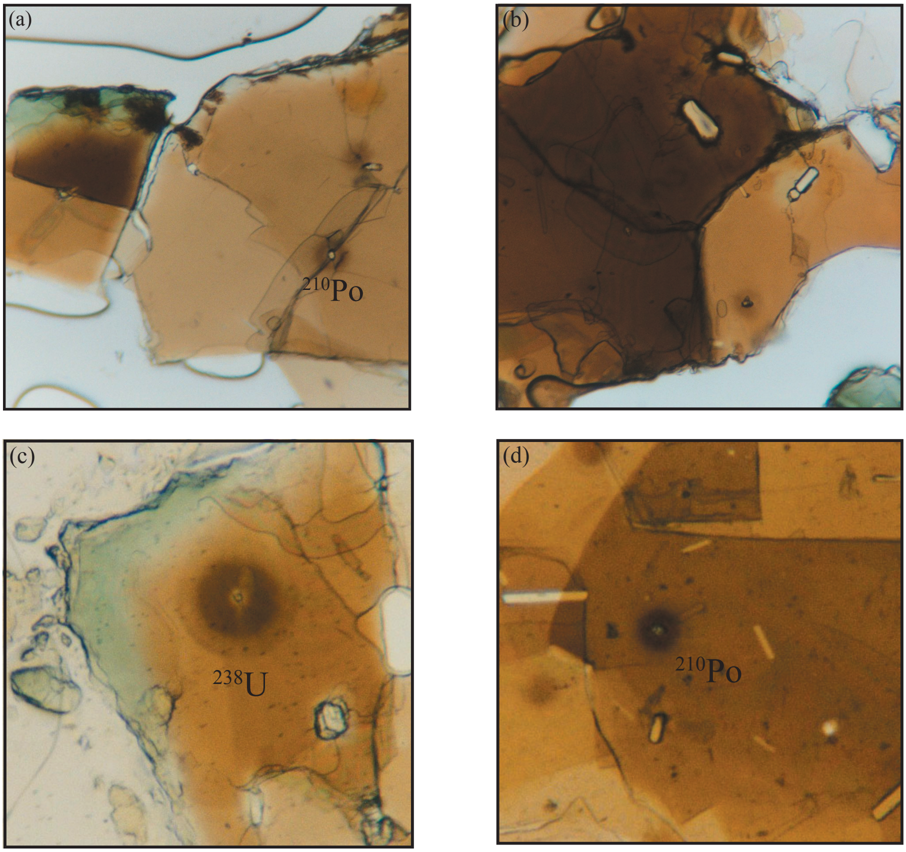


Figure 10. The effects of hydrothermal fluids on biotite. (a) (c) chloritization (b) (d) fluid inclusions (bubbles) in the cleavage planes between biotite sheets. Note the ^{210}Po radiohalos (diameter ~39 µm) centered on the crack in (a) and near fluid inclusions in (d), and the normal well-exposed ^{238}U radiohalo diameter ~70 µm) in (c). The fluid inclusions are ~50 µm long in (b) and up to ~100 µm in (d) (Shap Granite).

imperfections, and where the chemical environment was conducive to Po being concentrated to form discrete radiocenters. Furthermore, as the above calculations have shown, concentrations of ions such as S of only 10^6 atoms would have been required to combine with the Po isotopes being transported in the hydrothermal fluids to hold sufficient Po isotopes in the radiocenters to generate the Po radiohalos. Such an accumulation of S atoms, for example, would form a sub-microscopic inclusion in the biotite, similar to the native Cu inclusions observed by *Ilton and Veblen* [1988]. This would explain why almost all observed Po radiohalo centers appear to be simply empty minute spots. As the concentrated Po atoms subsequently α-decayed, further fluid flow delivered more Po atoms to the radiocenters where the S, metal and/or other ions that had scavenged the Po from the passing fluids had become free to scavenge more Po. Thus as discussed earlier, the required ring density is reached by accumulation over a period of time, calculated to be approximately 1.5 hours or more, during which fluid flow continues, the supply of Po atoms is available, and the chemical environment is conducive to the Po being concentrated in the radiocenters.

The end product of the ^{238}U decay chain, including the three Po isotopes, is ^{206}Pb, which is therefore present in the radiocenters of Po radiohalos [*Gentry*, 1974; *Gentry et al*., 1974]. Because Po also has a geochemical affinity for Pb [*Bagnall*, 1957], this Pb would also have assisted the concentration of further Po. Once all the Po α-decayed, the Pb and S atoms left in the radiocenters should have formed PbS (galena). So why is such galena not still visible in the Po radiohalo centers? As already indicated, the quantity of S and Pb atoms involved is relatively small, so that the resultant PbS radiocenters would be sub-microscopic and thus not readily visible. However, there could be an alternative explanation. As long as there was an abundant supply of Po in the hydrothermal fluid flow the S atoms would have preferentially bonded with the Po, because Po has a higher electron affinity than Pb [*Aylward and Findlay*, 1971]. Any Pb atoms not bonded to Po atoms would have been dissolved in the passing hydrothermal fluids and removed from the radiocenters. Once the supply of Po in the hydrothermal fluids diminished as the decay of ^{238}U decelerated, PbS would rarely have formed in the radiocenters. Instead, the Pb and S ions would have been flushed out of the radiocenters by being dissolved in the flowing hydrothermal fluids. Whereas the chemical environment in coalified wood was conducive for the Pb, S, and Se to be retained in the Po radiohalo centers [*Gentry et al.*, 1976b], without Po present in the radiocenters the biotite cleavage planes in granitic rocks were no longer able to retain the Pb and S atoms. Even at very low temperatures the chemistry of hydrothermal fluids enable them to dissolve and transport S, Pb, and other metals [*Garven and Raffensperger*, 1997]. This could be the likely explanation for the absence of mineral inclusions in almost all Po radiohalo centers.

Appendix B: Why the Variations in Abundances of the Radiohalos?

B.1 The Observed Abundances of the Radiohalos

It is immediately evident from Tables 1, 2, and 3 that there are enormous differences in the abundances of radiohalos between the different granitic rocks, ranging from no radiohalos at all to more than 10 radiohalos per slide in the Precambrian (pre-Flood) granitic rocks (Table 1); from no radiohalos at all to more than 250 radiohalos per slide in Paleozoic-Mesozoic (Flood) granitic rocks (Table 2); and almost no radiohalos in the Tertiary (post-Flood?) granitic rocks (Table 3). Of course, the lack of radiohalos in the Tertiary granitic rocks is probably due to there being insufficient time for sufficient α-tracks to accumulate and register as radiohalos. Given that a fully-formed radiohalo requires up to an estimated 100 million years worth (at today's rates) of nuclear decay, observable radiohalos would not be expected in Tertiary, and even latest Cretaceous (Table 2), granitic rocks. However, the question remains as to why there are such variations in the abundances of radiohalos in all the earlier granitic rocks.

Indeed, *Gentry* [1968] estimated that there may be as many as 20,000–30,000 ^{218}Po and ^{210}Po radiohalos per cm^3 in biotite in a Norwegian Precambrian granitic pegmatite (without any ^{214}Po radiohalos). *Gentry* [1975] stated that as many as 1000–50,000 ^{214}Po and ^{218}Po radiohalos often occur in some minerals, while he [*Gentry*, 1999] estimated that there are more than one billion U and Po radiohalos in the fluorite of the Phanerozoic vein at Wölsendorf in Germany. *Gentry* [1998] also pointed out that if the Po radiohalos formed by a secondary process from U-decay products, because of the different Po-isotope half-lives there would be greatly different quantities of each isotope co-existing. The amounts existing should be proportional to the respective half-lives. At any given time the atomic ratio of ^{210}Po to ^{218}Po should be 67,000:1, and thus there should be about 67,000 ^{210}Po radiohalos for each ^{218}Po radiohalo. Such proportions are not found. In the granitic rocks listed in Tables 1 and 2, there are always more ^{210}Po radiohalos than ^{218}Po radiohalos (the ^{210}Po:^{218}Po ratios varying from 4.8:1 to 1366:1). Clearly, the proportions of the different Po radiohalos vary from sample to sample. Compared to the granitic rock samples listed in Tables 1 and 2, *Meier and Hecker* [1976] found a distribution in a Norwegian biotite they studied of more than 1000 ^{210}Po radiohalos, 90 ^{218}Po radiohalos, and only one ^{214}Po radiohalo, yet Gentry reported to *Feather* [1978] that abundance ratios for other samples of biotite were ^{218}Po>^{210}Po>^{214}Po, and even ^{214}Po>^{218}Po or ^{210}Po.

So how can these different abundances and proportions of radiohalos be explained? In the one instance where Gentry demonstrated that ^{210}Po radiohalos had formed as a result of secondary fluid transport [*Gentry et al.*, 1976b], 100 or more ^{210}Po radiohalos were sometimes evident in a single thin section (2 cm by 2 cm) of coalified wood, and they occurred quite generally in the thin sections examined. Such an abundance is similar to that found in the Permian Land's End Granite of Cornwall in England, and not unlike the abundance of radiohalos found in the Devonian Strathbogie Granite of Victoria, Australia, and the Ordovician Encounter Bay and Palmer Granites of South Australia (Table 2). It should be noted that all the samples of this study (Tables 1 and 2) are just normal granitic rocks with a biotite abundance of 1–5%, and with the small biotite flakes evenly scattered through the fabric of the rocks. However, in contrast, the spectacular abundances of radiohalos of thousands or more per cm^3 reported by *Gentry* [1968, 1975, 1999] are found in large (10 or more cm^3) biotite and fluorite crystals in granitic pegmatites and calcite-biotite, calcite-fluorite, or fluorite veins (see Tables 4 and 5 of *Snelling* [2000] after *Wise* [1989]).

B.2 Why the Huge Radiohalo Abundances in Granitic Pegmatites and Veins?

Unlike the granitic plutons sampled for this study, that typically extend over areas of 100–1000 km^2, granitic pegmatites occur as dike-like bodies that are 1–50 m wide and 100–1000 m long, while veins are generally far more restricted in size. Both granitic pegmatites and veins form from the fluids in a residual melt late in the crystallization of a granitic pluton; and also form from local melting and recrystallization in high-grade metamorphic terranes [*Cerny*, 1982; *Jahns*, 1982; *London*, 1996]. They are characterized by large crystals (large concentrations) of rare minerals that contain volatile elements such as F, and rare elements such as the rare earth elements, Y, Th, U, Zr, Hf, Nb, Ta, Sn, etc., that precipitated from large volumes of hydrothermal fluids saturated in these elements. In the past it was frequently assumed that the presence of these large crystals in pegmatites and veins implied slow growth over long periods of time. This is now known to be a total misconception [*Luth*, 1976, pp. 405–411; *Wampler and Wallace*, 1998]. In fact, it has been demonstrated that the rate of nucleation is the most important factor in determining growth rates and eventual sizes of crystals [*Lofgren*, 1980; *Tsuchiyama*, 1983]. At the point of aqueous vapor saturation of a granitic melt, crystal fractionation can occur, so that volatiles are concentrated in a mobile vapor (hydrothermal)-residual melt phase which readily migrates into open fractures within the wall-rocks immediately adjacent to a granitic pluton, sometimes within the granite itself, or within host high-grade metamorphic rocks [*Jahns and Burnham*, 1969]. There the giant crystals (sometimes meters long) in pegmatites grow rapidly at rates of more than 10^{-6} cm per second [*London*, 1992] from the hydrothermal fluid in the residual melt phase saturated in volatiles, as the wide pegmatite vein rapidly cools [*Chakoumakos and Lumpkin*, 1992].

Thus, the formation of granitic pegmatites in wide veins with large crystals requires large volumes of hydrothermal fluids, which are also capable of transporting large quantities of U-decay products, such as ^{222}Rn and the Po isotopes. The first factor that would be responsible for the variations in the abundances of the Po radiohalos would be the volume of hydrothermal fluid flow. The larger the volume of hydrothermal fluids, the more radiocenters that could potentially be supplied with Po isotopes. A meager hydrothermal flow would produce few Po radiohalos.

There also must be a sufficient supply of U-decay products. As first noted by *Wise* [1989], all of the granitic pegmatites and veins that Gentry reported as containing such huge numbers of Po radiohalos in their large biotite (and fluorite) crystals are associated with large concentrations of U in visible mineralization and economic ore bodies (see Tables 4 and 5 of *Snelling* [2000] after *Wise* [1989]). *Wakefield* [1988a, b] and *Wilkerson* [1989] reported that the calcite-fluorite vein hosting the Po radiohalo-bearing biotite at the Fission Mine in Ontario, Canada, also contained cubic crystals and irregular masses of uraninite (primarily UO_2). This uraninite was found in cavities with the biotite in which the large numbers of Po radiohalos were found. The granitic pegmatite hosting the Po radiohalo-bearing biotite at the Faraday Mine, Ontario, Canada, also hosts uraninite and other U minerals. At the Silver Crater Mine, also in Ontario, Canada, the calcite-biotite vein with the Po radiohalo-bearing biotite also contains betafite (a complex U, rare earth element and F-bearing mineral). The betafite is often found as small crystals in close association with clusters of books of biotite, and even within the books themselves [*Wakefield*, 1988b]. Furthermore, the Wölsendorf fluorite district in northeast Bavaria, Germany, is well known for the U mineralization it contains, the fluorite veins being considered hydrothermal in origin and hosting uraninite, pitchblende, and coffinite [*Strunz and Seeliger*, 1960; *Ziehr*, 1980; *Dill*, 1983; *Carl and Dill*, 1985]. All the known fluorite veins with U mineralization occupy major joint systems that are tectonically controlled, and provide easy access for hydrothermal fluids [*Fürst and Bandelow*, 1982]. Finally, even the Kragero Precambrian granitic pegmatite in Norway in which *Meier and Hecker* [1976] reported large numbers of ^{210}Po radiohalos also has evidence within the biotites of high concentrations of U. They documented fractures along which there was evidence of both U and ^{210}Po having been transported by flow of hydrothermal fluids. Thus, in each of these instances of reported occurrences of high numbers of Po radiohalos, it can be shown that there were high concentrations of U, and therefore its decay products, adjacent to the host biotite and the fluorite crystals. Where there are higher numbers of Po radiohalos there was a ready source of an associated larger amount of U-decay products.

The third and final factor that could have a bearing on the huge numbers of Po radiohalos reported in some granitic pegmatites and veins is the availability of sufficient numbers of sites chemically conducive to Po isotope deposition. As already indicated, granitic pegmatites typically contain minerals, sometimes in large crystals, containing metals and other elements that are of economic importance. There are many elements in trace amounts that would be carried by the hydrothermal fluids into lattice defects and other sites along biotite cleavage planes to locations that would serve as depocenters for Po isotopes. An element common to the Canadian veins as well as the Wölsendorf vein is the halide F, which is sufficiently abundant to form fluorite crystals. It is significant that not only does Po dissolve in hydrothermal fluids with halides, but halides such as F can be accommodated in the biotite crystal lattice adjacent to the cleavage planes where it could serve as a scavenger of Po isotopes from hydrothermal fluids passing by. Furthermore, in the case of the Wölsendorf fluorite veins, which probably contain the greatest abundance of Po radiohalos, as well as U minerals per unit volume, the veins contain significant quantities of other metals and elements including Se [*Dill*, 1983]. This is significant because Se is an element with which Po has a geochemical affinity, and it was Se that *Gentry et al.* [1976b] found in the radiocenters of the ^{210}Po radiohalos in the coalified wood, radiohalos that Gentry agrees are of secondary origin due to fluid transport of Po. Thus there is good evidence that in each instance where there are extremely high numbers of Po radiohalos, there was an ample supply of suitable other elements to form the required nucleation centers. Therefore, all three essential components necessary for hydrothermal fluid transport of ^{222}Rn and Po isotopes to generate the abundant Po radiohalos in each of these geological contexts were in place.

B.3 Why the Lower Radiohalo Abundances in Granitic Rocks?

The conclusion from the foregoing discussion is that the abundance of Po radiohalos will be determined by the availability of ^{238}U and its decay products, the volume of hydrothermal fluid flow, and the availability of depocenters. In the examples just discussed where there are huge numbers of Po radiohalos, there are large concentrations of nearby U in mineralization and in oxide minerals from which the ^{238}U decay products are easily removed. There also were huge volumes of hydrothermal fluids able to transport the abundant ^{238}U decay products. On the other hand, in the granitic rocks in this study, as far as is known, the only source of ^{238}U decay products is the zircon grains whose U contents, and therefore the availability of ^{238}U decay products, is much lower than in U oxide minerals. So no matter how large a volume of hydrothermal fluids is available, if there is a poor supply of ^{238}U decay products, there will be a lower abundance of Po radiohalos. This could especially apply to the Precambrian (pre-Flood) granitic rocks in which the abundances of Po radiohalos are generally lower than their abundances in the Paleozoic-Mesozoic (Flood) granitic rocks (compare Tables 1 and 2). One possible explanation is the longer history of these Precambrian granitic rocks. Uranium-238 decay products could have originally been transported by hydrothermal fluids in the waning stages of the formation of these rocks, but when the Po radiohalos formed then were annealed by a subsequent heating event during the Flood, there was a lower residual abundance of ^{238}U decay products from which replacement Po radiohalos could be generated. The zircon grains in the Paleozoic-Mesozoic granitic rocks have suffered from only one "flushing" by hydrothermal fluids removing their ^{238}U decay products during the Flood. So if the zircons in the Paleozoic-Mesozoic granitic rocks that formed during the Flood had a greater availability of ^{238}U decay products than the Precambrian granitic rocks had at the time of the Flood event, there is a ready explanation for the general greater abundance of Po radiohalos in the Paleozoic-Mesozoic granitic rocks compared to the Precambrian granitic rocks.

The higher abundance of Po radiohalos in one of the Paleozoic-

Mesozoic granitic plutons, namely, the Land's End Granite in Cornwall, England (Table 2), is particularly significant, and further details of the geological context of that pluton are illustrative of how the Po radiohalo abundance is affected by the availability of the ^{238}U decay products and the volume of hydrothermal fluid flow. The Sn deposits of Cornwall in lodes within fracture systems in, and associated with, granitic plutons are well known and famous, but it is not as well known that there are also base metal and U deposits associated with these granitic plutons [*Willis-Richards and Jackson*, 1989; *Jackson et al.*, 1989]. There is a large list of occurrences of U minerals (uraninite, pitchblende, and many secondary U minerals) in these granitic rocks, including the Land's End Granite [*Rumbold*, 1954], and these have been used to U-Pb date the Sn and base metal lodes containing them [*Darnley et al.*, 1965]. Indeed, the Land's End Granite is now regarded as a chemically specialized granite that was emplaced at the end of the development of the Cornubian Batholith, and its Sn, base metal and U lodes developed from the hydrothermal fluid flow generated during the cooling of the pluton [*Chesley et al.*, 1993]. Furthermore, fluid inclusion studies of the mineralized veins have shown that large volumes of hydrothermal fluids circulated through the granitic plutons of the batholith and through fractures into the surrounding host rocks, generating the mineralized veins over a protracted period [*Gleeson et al.*, 2000, 2001]. Hydrogen and oxygen isotope studies of the granites and hydrothermally-altered minerals associated with the mineralized lodes indicate that the hydrothermal fluids were derived both from the magmatic waters of the granitic intrusions and from meteoric waters in the host rocks [*Sheppard*, 1977]. The picture that emerges from all of these studies is that the Land's End Granite, and the other granitic plutons of the Cornubian Batholith, when emplaced contained significantly elevated levels of not only Sn and base metals, but also U, and the prolonged hydrothermal activity that circulated through these granitic plutons carried the U with them to precipitate U minerals in the lodes within fracture zones. The circulating hydrothermal fluids would also have carried ^{238}U decay products together with the dissolved U. There is then a ready explanation for the significantly higher number of Po radiohalos in the Land's End Granite compared to the other Paleozoic-Mesozoic (Flood) granitic rocks in Table 2.

Several other observations and considerations are also relevant. First, another factor that could result in differences in the abundances of the Po radiohalos in the granitic rocks in this study is the abundance of zircon grains in them. Though the Po radiohalos usually outnumber the ^{238}U radiohalos, it is still evident that where there are more ^{238}U radiohalos there are also more Po radiohalos. The abundance of ^{238}U radiohalos is an indication of the abundance of zircon grains in the granitic rock; the more zircon grains there are, the more ^{238}U decay products are available to the hydrothermal fluids, and the more Po radiohalos are formed.

Second, several other factors could explain the different abundances of the various Po radiohalos in these granitic rocks. A primary factor would have to be the distance between the zircon source and the radiocenter where the Po isotopes are deposited. The greater the distance, the more likelihood that only ^{210}Po would survive hydrothermal fluid flow. Generally there are more ^{214}Po radiohalos than ^{218}Po radiohalos. Evidently the emission of a 7.69 MeV ^{214}Po α-particle (average 164 microseconds) immediately after a ^{218}Po α-decay often leaves the previous 6.00 MeV α-track indiscernible. Another factor that must affect the abundances of ^{218}Po and ^{214}Po radiohalos is the timing of both the arrival of the ^{222}Rn and ^{218}Po at the surfaces of the zircon grains after their diffusion out of their crystal lattices, and of the α-decay of ^{222}Rn into ^{218}Po along the hydrothermal fluid flow path within the biotite cleavage planes. If a ^{222}Rn atom has diffused to the surface of the zircon grain within one day of its coming into existence by α-decay of ^{226}Ra, then on average it will still have 2.8 days in which to transit in the hydrothermal fluid flow before α-decaying to ^{218}Po that is then deposited at a radiocenter to generate a ^{218}Po radiohalo. On the other hand, if it has taken the ^{222}Rn three days from the beginning of its existence to diffuse out of the zircon crystal, then it only has on average less than a day for transit in the hydrothermal fluid flow before α-decaying to a ^{218}Po atom. Obviously, because α-decay is a statistical process there will be ^{222}Rn atoms diffusing out of the zircon grains at all different times in their half-lives, but this will affect, in combination with the transit distances to the Po radiocenters and the rate of hydrothermal fluid flow, just which Po isotope will be deposited at the radiocenters and thus generate the respective Po radiohalos. Of course, an allied factor will be the overall state of crystallinity of the zircon grains, because if the zircon crystal structure has suffered radiation damage and become metamict, then diffusion will be more rapid. Indeed, if ^{238}U decay was accelerated there would be dramatically increased stress on the zircon crystal structure so that severe radiation damage would be quickly produced, thus allowing even greater diffusion rates. So variations in the amount and extent of radiation damage and metamictization will determine the rate at which ^{222}Rn and ^{218}Po atoms diffuse out of the zircon grains, and this then relates to the considerations discussed immediately above. Thus all these factors taken together will affect the resultant abundances of the different Po radiohalos, and of course all these factors will be different in each of these granitic rocks.

Appendix C. The Heat Problem

As has been shown already in Appendix A.5, the existence of the Po radiohalos in these granitic rocks, especially the ^{218}Po and ^{214}Po radiohalos because of the extremely short half-lives of these isotopes, has a direct implication as to the timescale for cooling of these granitic plutons. The survival of the Po isotopes and formation of these Po radiohalos places a severe timescale limit of six to ten days on the cooling of granitic plutons from 400°C or more down to the ambient temperatures at the near-surface crustal levels at which these plutons have been emplaced. This results in the problem of removing the enormous quantity of heat involved from the huge volume (specifically of the order of 200–500 km^3) of each granitic pluton within six to ten days. Such removal requires heat dissipation at least six orders of magnitude greater than currently postulated by conventional wisdom [*Petford et al*., 2000]. However, the existence of the Po and ^{238}U radiohalos together, if generated concurrently, implies nuclear decay had to have been accelerated, by probably at least six orders of magnitude during the Flood year. The enormous amount of heat generated by this accelerated nuclear decay adds considerably to the heat problem.

To put this heat problem in perspective we can quickly do a rough estimate of the effect of just the accelerated nuclear decay, say 500 million years worth (at today's rates), but instead taking place in a single year (the Flood year). The following values of the relevant parameters were obtained from *Stacey* [1992]:

- the typical heat production in a granitic pluton from radioactive decay of U, Th, and K is ~10^{-9} W/kg,
- the specific heat of granite is ~700 J/kg-K, and
- the number of seconds in 500 million years is ~1.6×10^{16} sec.

Thus the adiabatic temperature rise =

$$\left(\frac{(1.6\times10^{16}\ \text{sec})\times(10^{-9}\ \text{W/kg})}{700\ \text{J/kg-K}}\right)$$
$$= 22,400\text{K}$$

This is equivalent to a temperature rise of more than 22,000°C, which is sufficient, of course, to vaporize a granitic pluton many times over!

Another approach is to assess the heat production in the zircons themselves within the granitic rocks. Note that the U concentrations in the zircon grains can be on the order of 1% by mass of the grains. If the mass of a zircon grain relative to the mass of the biotite crystal that includes it is 0.01, then with the current heat production from radioactive decay of U of 10^{-4} W/kg, the average heat production in the biotite enclosing that zircon grain is 10^{-8} W/kg, which is only an order of magnitude higher than the value used above for a typical granite. Thus the adiabatic temperature rise in the biotite as a result of 500 million years worth of accelerated radioactive decay is an order of magnitude higher than the value obtained for the granitic rock as a whole. Of course, the biotite crystal and the zircon grain included in it would be vaporized! So whichever way the calculation is made, there is no denying that there is a genuine heat problem associated with accelerated nuclear decay.

However, the reality of the existence of the Po and ^{238}U radiohalos in biotite crystals in granitic rocks is evidence that removal of all this heat has not been an insurmountable problem if there has been accelerated decay. Incredible amounts of heat must have somehow been removed rapidly by a process or processes that we have not yet discovered or understood, for otherwise these rocks and the radiohalos in them would have been vaporized!

This potential problem was already anticipated by *Humphreys* [2000], and had previously been highlighted by *Baumgardner* [1986]. All creationist models of young earth history have serious problems with heat disposal, because there is simply too much geological work that has to be done in too short a time. Of course, the perception that there is a problem with disposal of heat is based on our present understanding and observations of heat production from radioactive decay and of heat flow, which are then applied using uniformitarian assumptions to geological processes in the past. But if geological processes have not been uniform in their rate and operation in the past, the uniformitarian assumption to project the present back into the past does not apply. In a nutshell, the perception that there is a heat problem is based solely on our understanding of these processes in the present, our ignorance of what actually happened during the catastrophic upheaval of the Flood year, and the Scriptural restriction to young earth modeling.

However, we need to wrestle seriously with this heat problem, in case we are able to decipher what process or processes may have been operating in concert with the catastrophic geological processes of the Flood year, such as rapid cooling of granitic magmas. *Humphreys* [2000] has suggested a potential solution that involves the expansion of the fabric of space within the cosmos, a process that makes energy disappear! As *Humphreys* [2000, 2005] has explained, there is a well-understood but poorly publicized mechanism in general relativity that could account for this loss. The result of the relevant calculations used in that mechanism is that the radiation energy which is lost in an expanding universe is used up as work in aiding the expansion [*Robertson and Noonan*, 1968]. Further explanation and discussion of this potential solution is provided by *Humphreys* [2005]. Obviously, these issues require further eludication, but the fact remains that in a young earth model radiohalos provide evidence of accelerated nuclear decay and rapid cooling of granitic rocks.

Appendix D. Other Applications and Their Implications

D.1 Other Sources of Hydrothermal Fluids and Their Environments

As discussed earlier, hydrothermal fluids are not only generated in crystallizing granitic plutons that release magmatic fluids, but may incorporate connate and meteoric waters that are heated by magmatic intrusions and are mixed with magmatic fluids. Similarly, hydrothermal fluids can be generated by the deep burial of connate waters within sedimentary basins, and by regional metamorphism as minerals containing water react under increasing temperatures and pressures to produce new minerals and release that water. The hydrothermal fluids associated with magmatic intrusions, particularly granitic plutons, also involve heat from the intrusions that causes contact metamorphism in the host rocks immediately surrounding the plutons. In all of these geological situations involving hydrothermal fluids the extremely active nature of those fluids, due to what they carry in solution, transports metals down flow in rock strata and fractures to locations where the chemical environment is conducive to precipitation of metals and gangue minerals to form ore deposits. Thus the hydrothermal fluids encompass a wide spectrum of fluid sources, and have operated within many geological contexts throughout those periods of earth's history in which the strata record was accumulating. Thus there may be other geological contexts apart from granitic plutons in which hydrothermal fluids may have been responsible for the transport of ^{238}U decay products and the generation of Po radiohalos.

D.2 Metamorphism, Hydrothermal Fluids, and Radiohalos

Snelling and Armitage [2003] have already predicted these potential applications of the hydrothermal fluid transport model for the secondary formation of Po radiohalos to a wide spectrum of geological contexts. They predicted that Po radiohalos should be found not only in granitic plutons, but also in regional metamorphic rocks. As argued here, many granitic plutons containing Po radiohalos were derived from partial melting as a result of regional metamorphism during the Flood. In some instances, for example, the Cooma Granodiorite [*Snelling and Armitage*, 2003], the regional metamorphic rocks from which the granitic plutons were derived are still to be found adjacent to them, or associated with them. *Snelling and Armitage* [2003] demonstrated that the zircons, which were the source of the ^{238}U decay products that were transported by hydrothermal fluids to form the Po radiohalos, were originally detrital zircons in the sediments that were regionally metamorphosed to form the granitic plutons. In the case of the Cooma Granodiorite, ^{238}U and ^{232}Th radiohalos have been observed around zircon and monazite inclusions respectively in biotites within the surrounding high-grade metamorphic rocks [*Williams*, 2001]. These zircon and monazite grains evidently contain sufficient quantities of ^{238}U, ^{232}Th, and their decay products for formation of radiohalos. Therefore, if hydrothermal fluids have flowed through these metamorphic rocks during the regional metamorphism, during the generation of the granitic magma, and during the cooling of both the granitic pluton and the metamorphic terrane, then the passage of those hydrothermal fluids through the biotite crystals in the metamorphic rocks could easily have transported the ^{238}U decay products for generation of Po radiohalos. *Snelling* [1994a, b] has argued that the process of regional metamorphism can be explained by the circulation of hydrothermal fluids through sediment layers of differing mineralogy and composition. The minerals in the sediments were thereby transformed into new metamorphic minerals that are characteristic of each regional metamorphic zone observed in metamorphic complexes today. Such regional metamorphic zones are usually explained in terms of only temperature and pressure conditions operating over millions of years. Thus if Po radiohalos are present in regionally metamorphosed rocks, especially alongside of ^{238}U radiohalos in the same biotite grains, this would provide definitive evidence of the role of hydrothermal fluids in regional metamorphism, and of the timescale involved.

The presence of ^{238}U and ^{232}Th radiohalos in metamorphic rocks has been documented by *Rimsaite* [1967], *Nasdala et al.* [2001], and *Williams* [2001]; but so far there has only been tentative documentation of Po radiohalos in one high-grade metamorphic rock (a gneiss) [*Mahadevan*, 1927; *Gentry*, 1971; *Wise*, 1989]. Thus it would be worthwhile for a concerted systematic effort to be made to verify and document the geological distribution and occurrence of all types of radiohalos in all types of metamorphic rocks, given that hydrothermal fluids are also involved in contact metamorphism. The critical component required would be that the metamorphic rocks contain biotite grains, because these readily host radiohalos. But many other minerals are known to host radiohalos [*Ramdohr*, 1933, 1957, 1976; *Stark*, 1936]; so metamorphic rocks of differing mineral assemblages would need to be examined. While the focus of this study has been granitic rocks, in the course of fieldwork a few metamorphic rocks have been sampled because of their close association with, or relationship to, nearby granitic rocks. The radiohalos found in those samples are recorded in Table 4. These results demonstrate conclusively that Po radiohalos are present in metamorphic rocks in similar abundances and similar proportions of the different types, as in granitic rocks. Metamorphic rocks therefore warrant focused systematic studies, particularly where the rocks in the different metamorphic zones surrounding a granitic pluton are readily accessible, such as in the Cooma Metamorphic Complex surrounding the Cooma Granodiorite [*Browne*, 1914; *Joplin*, 1942; *Hopwood*, 1976; *Johnson et al*., 1994]. The observations of Po radiohalos in these metamorphic rocks suggest that they too were formed as a result of hydrothermal fluid transport of ^{238}U decay products, in the same way that the Po radiohalos form in granitic rocks. Tiny zircon grains with ^{238}U radiohalos around them are observed in most of these rocks; so there is an adequate supply of ^{238}U decay products. This also implies that hydrothermal fluids were actively circulating through these rocks, at least during the cooling phase of the metamorphism below 150°C.

Although further verification obviously requires more detailed studies, these observations are consistent with the model for regional metamorphism proposed by *Snelling* [1994a, b], that involves the circulation of hydrothermal fluids through deeply-buried sedimentary rocks to transform their minerals into those in the metamorphic rocks. As with the cooling of granitic plutons, because the formation of the Po

Table 4. Radiohalos recorded in regional metamorphic rocks.

Rock Unit	Location	"Age"	Samples (slides)	Radiohalos					Number of Radiohalos per slide	Ratios			
				^{210}Po	^{214}Po	^{218}Po	^{238}U	^{232}Th		^{210}Po:^{238}U	^{210}Po:^{214}Po	^{210}Po:^{218}Po	^{238}U:^{232}Th
Migmatite adjacent to Palmer Granite	South Australia	Ordovician	1 (51)	234	8	0	507	3	14.7	1.0:2.2	29.3:1.0	—	169.0:1.0
Biotite Garnet Eclogite	Stordal, Norway	Late Proterozoic	1 (50)	7	0	0	0	0	0.14	—	—	—	—
Metamorphic pegmatite	Steiggjelselva, Norway	Middle to Late Proterozoic	1 (50)	30	0	0	0	0	0.6	—	—	—	—
Gneiss (and pegmatite)	Hegland, Norway	Early Proterozoic	2 (100)	0	0	0	0	0	—	—	—	—	—
Gneiss (and pegmatite)	Arendal, Norway	Proterozoic	2 (100)	65	33	0	0	0	0.98	—	1.97:1.0	—	—
Gneiss	Sandbraten, Norway	Proterozoic	1 (50)	78	0	0	0	0	1.56	—	—	—	—
Gneiss	Gravfoss, Norway	Proterozoic	1 (50)	0	0	0	0	0	0	—	—	—	—
Vishnu Schist	Grand Canyon (USA)	1690–1710 Ma	8 (400)	7904	12	4	2376	0	25.7	3.3:1.0	659.0:1.0	1976.0:1.0	—
Rama Schist	Grand Canyon (USA)	1690–1710 Ma	2 (100)	574	0	0	54	0	6.3	10.6:1.0	—	—	—
Dyrkorn Gneiss	Sunnmøre, Norway	Archean	1 (50)	24	0	7	5	0	0.7	4.8:1.0	—	3.4:1.0	—
Gneiss	Ilomantsi, Finland	Archean	1 (50)	83	0	0	29	0	2.2	2.9:1.0	—	—	—

radiohalos requires extremely rapid cooling and extremely rapid flows of hydrothermal fluids, the similar presence of Po radiohalos in these metamorphic rocks must equally imply that they also cooled extremely rapidly, during which time there were extremely rapid hydrothermal fluid flows through them. During regional metamorphism temperatures can reach as high as 600°C or more; and at those temperatures connate waters contained in the original sediments and water derived from mineral reactions become hydrothermal fluids that would be driven by the heat originating in the center of the metamorphic complex. Up to these temperatures zircon grains will survive intact [*Williams*, 2001]; so as soon as the hydrothermal fluids flow past zircon grains they will transport ^{238}U decay products. As long as the temperatures in the newly formed metamorphic rocks are above 150°C there will be no α-tracks recorded or formation of radiohalos. Because of the 3.8 day half-life of ^{222}Rn and the brief half-lives of 3.1 minutes and 164 microseconds for ^{218}Po and ^{214}Po respectively, temperatures from the peak of metamorphism have to fall extremely rapidly to below 150°C for the Po radiohalos to form before the supply of ^{222}Rn and Po isotopes from the zircons is exhausted, and the hydrothermal fluid flow ceases. Because of these constraints, similar to those with granitic rocks, the time involved for this cooling process from the peak temperatures of metamorphism to ambient temperatures would have to be of the order of 6–10 days. Distances over which the ^{222}Rn and Po isotopes have to be transported must be short enough, and the hydrothermal fluid flows fast enough, for the Po isotopes to be deposited in the radiocenters. If only ^{210}Po radiohalos were in these rocks it could be argued that the cooling and transport process could have taken more time and been over longer distances; but the presence of ^{214}Po radiohalos (Table 4) restricts the time frame. Furthermore, as in the granitic rocks, the fact that both the ^{238}U and Po radiohalos must have formed concurrently after the temperatures had fallen below 150°C implies accelerated nuclear decay during the formation process. The observed fully-formed ^{238}U radiohalos represent up to 100 million years worth of ^{238}U decay at present rates.

It would seem to be very disappointing that the fiat Creation hypothesis for the formation of the Po radiohalos and their host granitic rocks has been falsified. However, the timescale considerations for the formation of Po radiohalos still remain, and they have implications for both the cooling of granitic plutons and metamorphic complexes that contain Po radiohalos. With accelerated nuclear decay the hydrothermal fluids that transport the ^{222}Rn and Po isotopes to form the Po radiohalos must also rapidly transfer an immense amount of heat from crystallizing granitic magmas, and away from the high-grade metamorphic zones to the outer limits of the metamorphic complexes [*Snelling*, 1994a; *Snelling and Woodmorappe*, 1998]. Thus it is contended that the presence of Po radiohalos in granitic and metamorphic rocks implies an extremely short timescale for their formation and cooling—just a few days, not weeks or years—a timescale consistent with the year of the catastrophic global Flood. Similar granite formation and metamorphic processes may have been associated with the Creation week. As with the Precambrian granitic plutons, metamorphic rocks that may date back to the Creation week most likely suffered from the heat flow evident during the tectonics of the Flood; and thus the ^{238}U and Po radiohalos now observed in these rocks may well date only from the Flood event.

D.3 Hydrothermal Ore Deposits and Radiohalos

Hydrothermal fluids have been also responsible for the deposition of many metallic ore deposits—fluids associated with emplacement of granitic magmas, and also fluids associated with regional metamorphism deep within sedimentary basins [*Barnes*, 1997]. Because the occurrence of Po radiohalos in granitic and metamorphic rocks implies rapid convective flows of hydrothermal fluids and also rapid cooling of those rocks, Po radiohalos found associated with hydrothermal metallic ore deposits imply rapid deposition of those ore deposits. For example, the higher abundance of Po radiohalos in the Land's End Granite of Cornwall, England (Table 2 and Figure 6), is not simply due to the large numbers of tiny zircon inclusions in the biotites of that granite. Other granites such as the Strathbogie Granite of Victoria, Australia, also have large numbers of zircon inclusions and ^{238}U radiohalos. Rather, the Land's End Granite radiohalos are also due to the additional U, and therefore also ^{238}U decay products, in the hydrothermal fluids carrying the Sn, Pb, Zn, Cu, etc. through the granite and out into the fractures where the metals were deposited in economic lodes. Similarly, the several pegmatitic veins (in Ontario, Canada) containing biotites with huge abundances of Po radiohalos also host economic U ore deposits, testimony to the hydrothermal fluid flows responsible for both the U ore and the Po radiohalos.

Thus the presence of Po radiohalos associated with such metallic ore deposits has the potential to show that these deposits were formed rapidly. This is a far-reaching implication, because it encompasses all major classes of metallic ore deposits, ranging from porphyry Cu±Au±Mo deposits hosted by granitic rocks to vein deposits of gold and other metals (such as in Cornwall, England), and to massive sulfide deposits containing base and other metals. Such deposits range in size from small to giant, and are found at many distinctive levels throughout the global geological record. Furthermore, a corollary to this is that in new areas that are being explored for hydrothermal metallic ore deposits it may be possible to use the presence and abundance of Po radiohalos as a guide to where there have been hydrothermal fluid flows in favorable host rocks to produce ore deposits. In areas where hydrothermal metallic ore deposits have already been found Po radiohalos could be used as an exploration tool to locate new ore deposits.

The presence of Po radiohalos has powerful and far-reaching implications—implications for the rapid formation of granitic plutons and regional metamorphic complexes, and also for the rapid deposition of metallic ore deposits. These processes would have occurred catastrophically on a global scale within the Flood year. It is possible that metallic ore deposits were also formed during Creation week, and in the pre-Flood world. The "fountains of waters" that operated in the pre-Flood world could have been outlets for hydrothermal fluids flowing deep within the earth's crust which could have deposited metallic ores both at depth and in near-surface locations.

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