Radiohalos—A Tale of Three Granitic Plutons

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Abstract

The origin and significance of radiohalos, particularly the ^{218}Po, ^{214}Po, and ^{210}Po radiohalos, have been debated for almost a century, perhaps largely because their geological distribution has been poorly understood. In this study samples from three granitic plutons were scanned under microscopes for radiohalos as part of a larger project to investigate the geological occurrence and global distribution of all types of radiohalos. These three granitic plutons were all demonstrated to have formed during the Flood, but all contained ^{210}Po, ^{214}Po, and ^{238}U radiohalos, usually with ^{210}Po >> ^{214}Po and ^{238}U; ^{218}Po radiohalos were rare, and ^{232}Th radiohalos were abundant in one granitic pluton. Thus neither the Po radiohalos nor the granitic rocks could have been formed by fiat creation. Instead, a model is proposed in which hydrothermal fluids separated ^{222}Rn and the Po isotopes from their parent ^{238}U in zircons and transported them very short distances along cleavage planes in the host, and adjacent, biotites until the ^{222}Rn decayed and the Po isotopes were chemically concentrated into radiocenters, there to subsequently produce the Po radiohalos. Furthermore, the very short half-lives of these isotopes require this transport process to be rapid (within days), and the observed fully-formed ^{238}U and ^{232}Th radiohalos imply at least 100 million years worth (at today's rates) of accelerated radioactive decay has occurred. Other implications include: accelerated heat flow during the Flood that helped catastrophically drive global tectonic and geological processes, including metamorphism and magma genesis; and rapid convective hydrothermal fluid flows that rapidly formed and cooled regional metamorphic complexes, rapidly cooled granitic and other plutons, and rapidly formed many metallic ore deposits.

Keywords

Radiohalos, ^{218}Po, ^{214}Po, ^{210}Po, ^{238}U, ^{232}Th, Granitic Plutons, Biotites, Zircons, Monazites, Hydrothermal Fluids, ^{222}Rn, Radiocenters, Accelerated Decay and Heat Flow, Rapid Hydrothermal Fluid Flows, Rapid Regional Metamorphism, Rapid Pluton Cooling, Rapidly Formed Metallic Ore Deposits

Introduction

Radiohalos are minute zones of darkening surrounding tiny central mineral inclusions or crystals in some minerals. They are best expressed in certain minerals in rock thin sections, 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 and Mügge 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. When observed in thin sections these shells are concentric circles with diameters between 10 and 40 μm, simply representing 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 in section 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 small (about 1 μm) the radiohalos around them have been unequivocally demonstrated to be the 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). ^{235}U radiohalos have not been observed. This is readily accounted for by the scarcity of ^{235}U (only 0.7% of 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 and/or ^{232}Th α-decay, irrespective of whether the actual halo sizes closely match the respective idealized patterns. 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). U 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 40 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 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 them have made biotite an ideal choice for numerous radiohalo investigations, namely, those of Gentry (1968, 1970, 1971), Henderson & Bateson (1934), Henderson & Turnbull (1934), Henderson & Sparks (1939), Henderson, Mushkat, & Crawford (1934), Iimori & Yoshimura (1926), Joly (1917a, 1917b, 1923, 1924), Kerr-Lawson (1927, 1928),Lingen (1926) and Wiman (1930). U, Th and other specific halo types thus far have been observed mainly in Precambrian rocks, but much remains to be learned about their occurrence in rocks from other geological periods. However, some studies have shown that they do exist in rocks stretching from the Precambrian to the Tertiary (Holmes, 1931; Stark, 1936; Wise, 1989). Unfortunately, in most instances the radiohalo types were not specifically identified in these studies.

Some unusual radiohalo types that are distinct from those formed by ^{238}U and/or ^{232}Th α-decay have been observed. Of these, only the Po (polonium) radiohalos can presently be identified with known α-radioactivity (Gentry, 1968, 1971, 1973, 1974; Gentry, Cristy, McLaughlin, & McHugh,1973; Gentry et al. 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). Po radiohalos contain only rings produced by these three Po α-emitters. 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 which produced these Po radiohalos initially contained either only 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 from granitic rocks (Gentry, 1968, 1971, 1973, 1974, 1984, 1986, 1988; Gentry et al., 1973, 1974; Wise, 1989).

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 Wölsendorf fluorite, he suggested that they originated from preferential deposition of Po from U-bearing solutions. Henderson (1939) and Henderson & Sparks (1939) invoked a similar but more quantitative hypothesis to explain Po radiohalos along conduits in biotite. Those Po radiohalos found occurring away from the conduits, similar to those found by Gentry (1973, 1974), were more difficult to account for. The reason for these attempts to account for 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 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, 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 more 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 those radiohalos, that is, Precambrian granites as he perceived them 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 has concluded that there are insufficient data on the geological occurrence and distribution of the Po radiohalos for the debate to yet be decisively resolved. Of the 22 locations then known where the rocks contained Po radiohalos, Wise (1989) 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, there are now significant reports of ^{210}Po as a detectable species in volcanic gases, in volcanic/hydrothermal fluids associated with subaerial volcanoes and fumaroles, and associated with mid-ocean ridge hydrothermal vents and chimney deposits (Hussain, Church, Luther, & Moore, 1995; Le Cloarec, Pennisi, Corazza, & Lambert, 1994; Rubin, 1997), as well as in ground waters (Harada, Burnett, La Rock, & Cowart, 1989; La Rock 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, 2000; Snelling & Woodmorappe, 1998).

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 year's 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 year's worth of radioactive decay at today's rates has occurred during earth history. As proposed by Humphreys (2000), these observable data require that within the biblical young-earth time framework radioisotopic 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 year's worth of radioisotopic 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.

A systematic effort to investigate radiohalo occurrences in granitic rocks throughout the geological record globally has thus been initiated (Vardiman, Snelling, & Chaffin, 2000). Initial focus has been on granitic plutons that intrude Flood strata and thus are considered to have formed during the Flood. Already Armitage (2001) has reported the discovery of ^{210}Po radiohalos in the late Carboniferous Stone Mountain granite near Atlanta, Georgia. Additional suitable samples have been collected from the Stone Mountain granite pluton for more detailed assessment of the radiohalo content of this pluton. Samples have also been collected along a traverse through the large mid-Cretaceous La Posta zoned granite pluton in the Peninsular Ranges Batholith east of San Diego, California. A sample has also been collected from the Silurian Cooma granite pluton which occurs at the center of a classic regional metamorphic complex in southern New South Wales, Australia.

The Stone Mountain Pluton

The Stone Mountain granite is a fine-grained, leucocratic quartz monzonite (Whitney, Jones, & Walker, 1976) or monzogranite (Le Maitre, 2001) intruded into sillimanite-grade schist and gneiss of the Inner Piedmont geologic province of Georgia, about 15–30 km east of Atlanta (Figure 1). It forms several prominent monadnocks, the most famous of which is Stone Mountain itself at the south-western extremity of the main exposure of the pluton (Figure 1), its steep north-facing slope being the Confederate Memorial, a carving of Lee, Jackson, and Davis (Grant, 1986). The pluton was first mapped in detail by Hermann (1954). Figure 1 is a simplified geologic map of the main body of the pluton.

The composition of the monzogranite averages about 30% quartz, 35% plagioclase (oligoclase), 25% K-feldspar (microcline), 9% muscovite, and 1% biotite, with a hypidiomorphic-granular to aplitic texture (Grant, Size, & O'Connor, 1980; Whitney et al., 1976; Wright, 1966). Characteristic accessories

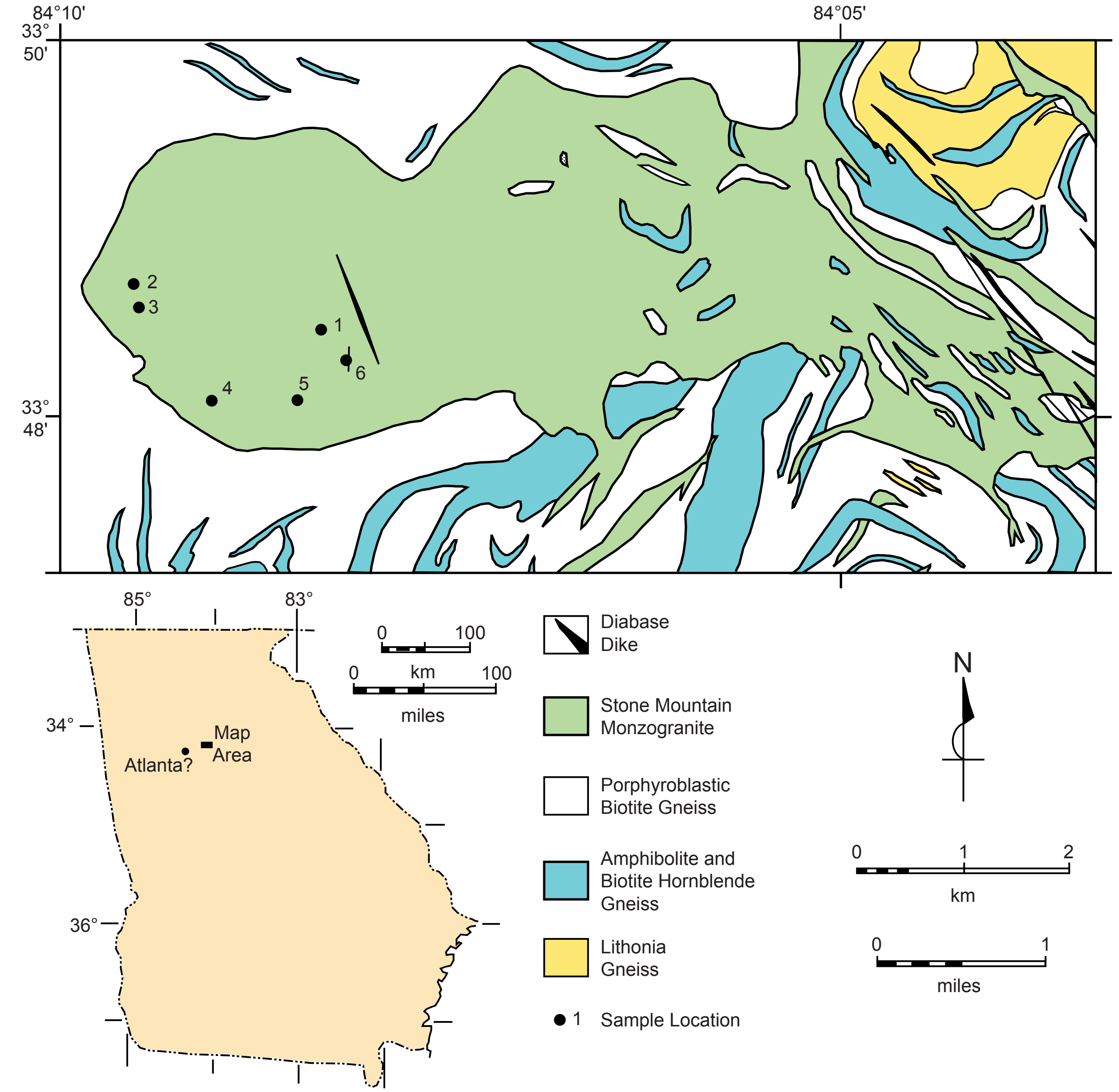

Figure 1. Geologic map of the main area of the Stone Mountain pluton, showing its location near Atlanta, Georgia, and the locations of the samples examined for radiohalos.

include epidote, apatite, zircon, and occasional tourmaline and garnet (almandine). Whitney et al. (1976) commented on the well-developed radiohalos around tiny zircon inclusions within biotite grains. The mineral grain sizes range from 1 to 4 mm, but the grain size distribution is uniform so the rock mass appears equigranular throughout the pluton, which is mineralogically quite homogeneous, with very little statistically meaningful variation throughout it (Grant et al., 1980; Whitney et al.). The intrusion is also noted for 2–5 cm long tourmaline-rich pods; and pegmatite, aplite, and composite dikes are common near the western margin of the pluton, while occurring sporadically throughout the rest of the intrusion. These appear similar in mineralogy to the rest of the intrusion, except tourmaline often occurs rather than biotite or muscovite (Whitney et al.).

The monzogranite intrudes both concordantly and discordantly into country rocks composed primarily of biotite-plagioclase gneiss, interlayered with pods of amphibolite, and minor mica schist (Grant, 1986; Hermann, 1954; Whitney et al., 1976). These rocks had been regionally metamorphosed to above the sillimanite isograd. At the monzogranite contact a slight grain-size enlargement occurs which is attributed to contact metamorphism (Grant, 1986). There is also some indication of contact metasomatism, which manifests itself as microcline porphyroblasts in the gneisses near the north monzogranite contact (Grant, 1962). The intrusion appears to cross-cut both the common isoclinal structures and more open folds in the surrounding regional metamorphosed rocks, structural evidence also suggesting that some parts of the pluton may have been forcefully intruded, deforming all previous foliations (Hermann, 1954; Whitney et al., 1976). Thus the contact and structural data indicate that the monzogranite intrusion was late metamorphic, confirmed by the crystal growth at contacts with pre-existing metamorphic mineral assemblages (Grant, 1986).

The Stone Mountain monzogranite itself has a moderate to poor foliation defined by the orientation of biotite and muscovite. This foliation is not concordant with the regional trends in the surrounding country rocks and appears to be parallel to megascopic flow features within the pluton (Hermann, 1954). Indeed, flow banding and flowage foliation within otherwise massive monzogranite is well documented by Grant (1986). Xenoliths are mostly lens-shaped mica schist fragments that show a strong orientation parallel to the flow structure. Biotite gneiss xenoliths are less common. Mapping of flow structures suggests that the pluton is a rather thin sheet, the intrusion of which was controlled by the dominant northwest-trending fold system in the surrounding country rocks (Atkins & Higgins, 1978; Grant, 1986). It is thus possible that the monzogranite was intruded through northwest-trending dikes in a number of pulses rather than a single episode (Hermann). Supporting this contention are monzogranite dikes which cross-cut earlier-formed monzogranite autoliths contained in the main monzogranite mass, all these monzogranites being of similar composition and only recognized by these textural and structural features. The distribution of lineations contained in the xenoliths support the contention that the granitic magma grew and expanded as it intruded between thin layers of simultaneously folding country rock (Grant, 1986).

Petrologic and geochemical data suggest that the origin of this peraluminous monzogranite is best explained by the anatexis of an older peraluminous, granitic crustal material (Whitney et al., 1976). The most likely source material is believed to be the Lithonia Gneiss, which has a peraluminous, granitic composition very similar to the Stone Mountain monzogranite and which underlies the area (Hermann, 1954). The Stone Mountain intrusion thus probably originated as a low-temperature anatectic melt formed from fractional melting of a part of the Lithonia Gneiss at a temperature of 700°C or less at depths of 22–28km, depending on the regional geothermal gradient at the time (Whitney et al.). During the process the availability of water would have been an important factor in determining the degree of melting. Once generated the magma was probably intruded at a depth of around 12km.

Radioisotopic ages determined from the Stone Mountain pluton are in the range 281–325Ma (Atkins, Higgins, & Gottfried, 1980; Dallmeyer, 1978; Whitney et al, 1976). Whitney et al. obtained an Rb-Sr isochron from 10 whole-rock and three mineral samples (plagioclase, microcline, and biotite) which yielded an age of 291±7Ma, making the intrusion latest Carboniferous. On the other hand, Dallmeyer found that $^{40}Ar/^{39}Ar$ age spectra of biotite and muscovite from the Stone Mountain monzogranite were undisturbed, both minerals recording similar total-gas ages (biotite 281±5Ma, muscovite 283±5Ma). These ages were regarded as anomalously younger than those recorded by biotite and hornblende within the adjacent gneisses, so it was suggested that these “ages” represent rapid post-magmatic cooling below argon retention temperatures. Thus the 291Ma date for the Stone Mountain monzogranite is the recognized “age,” temporally relating it to a belt of other granitic plutons in the Piedmont of the southeastern Appalachians, primarily in North and South Carolina (Fullagar, 1971). The postulated source for the magma, the Lithonia Gneiss, has yielded conventional K-Ar ages from its micas of 310–315Ma (Fairbairn, Pinson, Hurley, & Cormier, 1960; Pinson et al., 1957) (probably the onset of regional metamorphism), whereas zircons have yielded U-Pb ages of about 480Ma (Grunenfelder & Silver, 1958) (zircons probably inherited from the original sediments).

Both McQueen (1986) and Froede (1995) place the formation of the Stone Mountain monzogranite pluton within the year of the Flood. Furthermore, Froede (1995, 1997) has documented much evidence consistent with rapid emplacement and cooling of the granitic magma within the Flood year prior to the massive amounts of erosion at the end of the Flood that stripped the overlying country rocks to leave the pluton exposed today at the earth’s surface.

The La Posta Pluton

The La Posta pluton is located approximately 65km east of San Diego, California, in the Peninsular Ranges Batholith and straddles the international border with Mexico (Figure 2). The Peninsular Ranges Batholith is an elongated body of igneous rocks, consisting of hundreds of plutons, averaging about 100km in width that extends nearly 1000km from the Transverse Ranges near Riverside, southern California, to about the 28th parallel in Baja California, Mexico. It has been subdivided along a major discontinuity into western and eastern zones that parallel the long axis of the batholith (Gastil, 1975; Gastil et al., 1990; Todd & Shaw, 1985). The

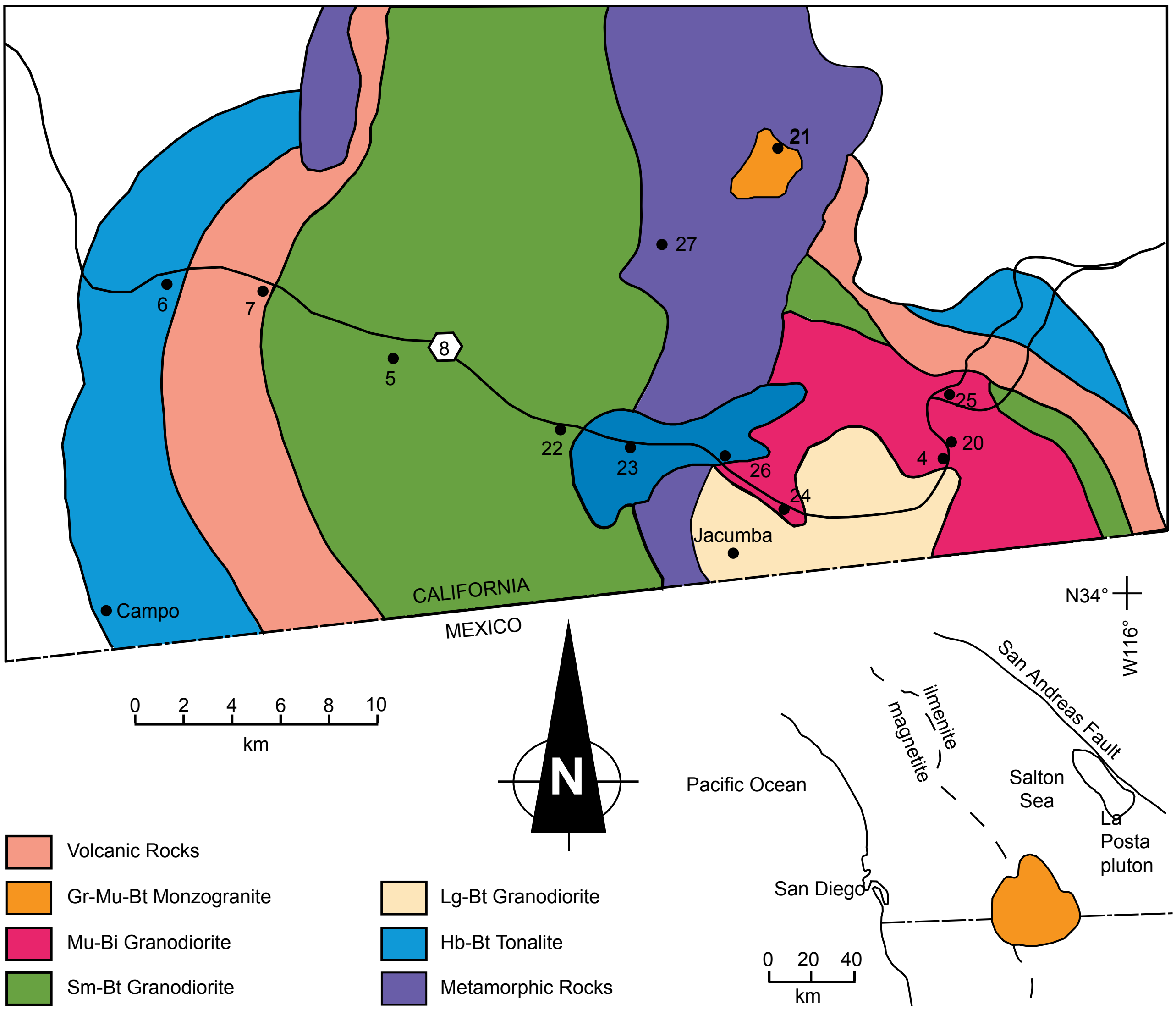

Figure 2. Geologic and location maps for the La Posta pluton, Peninsular Ranges Batholith, southern California, showing the different facies of this zoned pluton and the sampling locations.

western zone is characterized by small plutons that are generally less than 100 km^2 in exposed area, pluton compositions ranging from peridotite to granite with tonalite being most abundant, the presence of gabbros, and moderate grades of metamorphism in the host rocks (Walawender et al., 1990, 1991). This contrasts with the larger plutons, typically several hundred km^2 in size, with a more limited range of compositions (tonalite to monzogranite), and no gabbro in the eastern zone intruded into sillimanite-bearing and migmatitic pre-batholithic rocks. The boundary between these eastern and western zones is a major discontinuity defined by an I-S line separating I-type granitoids to the west and both I-type and S-type granitoids to the east (Todd & Shaw, 1985), and a magnetite-ilmenite line which effectively separates magnetite- and ilmenite-bearing plutons to the west from the plutons to the east in which the only opaque phase is ilmenite (Gastil et al., 1990). Additionally, Todd & Shaw (1979) recognized that the plutons of the western zone are synkinematically deformed and were thus syntectonically emplaced, whereas the eastern zone plutons are essentially undeformed and thus are late- to post-tectonic intrusions. Finally, there is a significant difference in the ages of the plutons either side of this discontinuity through the batholith, the western zone plutons yielding emplacement ages from 140 to 105 Ma, while the eastern zone plutons were emplaced from 98 to 89 Ma (Silver & Chappell, 1988; Walawender et al., 1990), interpreted as two distinct periods of static-arc magmatism resulting from an eastward migration of the locus of magmatism.

The largest intrusion in the eastern zone of the batholith is the La Posta pluton, with an estimated exposure area of 1400 km^2. Approximately 750 km^2 of this pluton have been mapped and studied in detail (Figure 2) (Clinkenbeard, 1987; Kimzey, 1982). It has thus been established that the pluton is a single intrusive body produced by a single magmatic pulse that crystallized inward to form a lithologic succession of concentric zones ranging from a sphene-hornblende-biotite tonalite rim to a muscovite-biotite granodiorite core (Figure 2). A banded border facies up to 100 m wide, not shown in Figure 2, consists of alternating bands rich in hornblende (± biotite) and plagioclase (± quartz) which are locally and discontinuously developed along contacts with the older igneous rocks of the western zone of the batholith (Clinkenbeard & Walawender, 1989; Walawender et al., 1990). Actually, the pluton is massive, the absence of foliation being noteworthy. It is only foliated near its margins or near metasedimentary roof pendants where the foliation is steep and parallel to contacts. The sphene-hornblende-biotite tonalite found in the outer zone (hornblende-biotite facies) consists of large (up to 1 cm), inclusion-free hornblende euhedra, pseudo-hexagonal books of biotite, and smaller (up to 0.5 cm) honey- to amber-colored prismatic sphene crystals. Plagioclase is the most abundant phase and displays mild oscillatory zoning. Quartz occurs as discrete anhedral grains with weakly developed undulatory extinction. The rock becomes progressively more enriched in interstitial K-feldspar and depleted in hornblende inwards.

All the contacts between these internal zones of the pluton are gradational over distances of several tens of meters (Walawender et al., 1990, 1991). The hornblende-biotite facies grades inwards to the large-biotite facies, a sphene-biotite granodiorite, by gradual loss of the large hornblende euhedra and increase in oikocrystic feldspar. The large-biotite facies is characterized by its abundance of large (up to 1 cm) pseudohexagonal books of biotite that impart a distinct "salt and pepper" appearance to the outcrops. The transition into the small-biotite facies is observed as a gradual loss of the large biotite books and an increase in the amount of smaller (1 to 4 mm), but still euhedral, biotite grains. There also appears to be a general decrease in grain size in this unit, although the K-feldspar oikocrysts locally reach 5-cm widths. The muscovite-biotite facies core of the pluton (a muscovite-biotite granodiorite) is defined on the basis of visible muscovite in hand specimen, which ranges up to 1% and meets the textural criteria for being of primary magmatic origin (Miller, 1981). Sphene is absent in this facies. Ilmenite appears to be the sole opaque phase in all of the facies.

Multiple zircon fractions from three different samples within the pluton yield an U-Pb age of 94±2 Ma, although the data obtained also possibly suggest a small inherited Pb component (Clinkenbeard, 1987; Walawender et al., 1990). An Rb-Sr mineral isochron from one of these same samples, taken from the small biotite facies on the western side of the pluton, yielded a regression age of 92±2.8 Ma (the apatite, whole rock, and hornblende had comparable Rb-Sr and thus reduced the system to an effective two-point isochron). Nevertheless, the Rb-Sr regression age is consistent within the error margins with the average zircon U-Pb age, which indicates the placement of the pluton in the mid-Cretaceous.

Intrusive into the La Posta pluton and the large sillimanite-grade metasedimentary screen, elongated north-south across the center of the pluton dividing it into two parts (Figure 2), are two small garnet-muscovite-biotite monzogranite plutons (Clinkenbeard, 1987; Parrish, 1990; Walawender et al., 1990, 1991). The Indian Hill pluton, the smaller and more northerly of the two plutons (Figure 2), consists of two facies—the medium-grained garnet-muscovite-biotite monzogranite and a fine-grained muscovite-biotite granodiorite (Parrish). A sample of the garnet-muscovite-biotite monzogranite yielded a four-point Rb-Sr mineral isochron representing the crystallization age of 89.6±2.6 Ma, which is thus interpreted as the emplacement age for the pluton (Parrish; Walawender et al., 1990, 1991). Five zircon fractions from the same sample yielded discordant ages that plot on a chord with a lower concordia intercept age of 84.4±6.1 Ma and an upper concordia intercept age of 1161±430 Ma. This U-Pb upper intercept age is interpreted as representing the average age of the rocks which melted to form the Indian Hill pluton, and thus the zircons containing the Pb are also interpreted as inherited (Parrish; Walawender et al., 1990, 1991; Walawender & Girty, 1991). Significantly, the zircon grains within this pluton are recorded as being readily apparent as tiny inclusions surrounded by radiohalos within the biotite flakes (Walawender et al., 1991). In contrast, three zircon fractions from a sample of the larger garnet-muscovite-biotite monzogranite pluton to the south (Figure 2) yielded a concordant age of 93±1 Ma, an emplacement age that is consistent with the observed field relationships (Clinkenbeard).

Pegmatite dikes are common in the metasedimentary screen to the west of the Indian Hill pluton. This metasedimentary screen, and the Indian Hill pluton within it (Figure 2), is in fact a roof pendant within and above the La Posta pluton (Walawender & Girty, 1991). Limited field and isotopic data suggest that these dikes are genetically related to the garnet-muscovite-biotite (S-type) monzogranite plutons, which are in turn believed to have resulted from the anatexis of the metasedimentary rocks in the roof pendant to the La Posta pluton, the heat source being likely due to the emplacement of the La Posta pluton (Walawender & Girty; Walawender et al., 1991). During the partial melting of these metasedimentary rocks detrital zircon contained in them was incorporated in the partial melt and thus the resultant monzogranite plutons. Emplacement of the plutons is believed to have been preceded by injection of the pegmatite dikes (Walawender et al., 1991).

The most distinctive singular geochemical characteristic of the La Posta pluton is its high Sr content, which contrasts markedly with Sr abundances in the other plutonic rocks of the batholith, and this suggests a fundamental difference in the source region for its magma (Todd & Shaw, 1979; Walawender et al., 1990). Additionally, the rare earth element (REE) patterns of the La Posta rocks suggest that the pluton was derived by subduction-related anatexis of eclogite-facies basaltic oceanic crust (Gromet & Silver, 1987). Alternately, a source region of amphibolitic oceanic crust would also appear to satisfy the trace element and chemical constraints, provided that all plagioclase was removed from the source during the melting event to account for the high Sr abundance (Walawender et al., 1990). However, the presence of zircon in the La Posta pluton and in the spatially related but compositionally distinct garnet-muscovite-biotite monzogranite plutons, with U-Pb ages older than emplacement ages of these plutons, suggests inheritance of detrital zircon from a metasedimentary source, which in turn suggests contamination of the I-type La Posta magma subsequent to its derivation by partial melting of oceanic crust (Walawender et al., 1990). This would also account for the core of the pluton being S-type muscovite-biotite granodiorite. It has thus been suggested that the La Posta magmatic diapir ascended through the juncture of the older North American continental crust and oceanic lithosphere (Gastil, 1975), with the muscovite-biotite granodiorite core representing the tail of the diapir that had interacted with the leading edge of the North American continental crust prior to intruding into the head of the ballooning (?) La Posta diapir (Walawender et al., 1990, 1991). Viscosity differences between the parental La Posta melt and the contaminated tail would inhibit homogenization, so that inward crystallization would still produce the observed gradational contacts between the higher temperature outer facies and the lower temperature assemblage in the core. Marked changes in plagioclase compositions, and in Fe/Mg and Fe^{2+}/Fe^{3+} in biotites, between the core and outer zones (Clinkenbeard & Walawender, 1989) are consistent with this emplacement and crystallization model.

The Cooma Pluton

The Cooma granodiorite was first mapped by Browne (1914) and is a small, elliptical pluton centered approximately on the township of Cooma in southern New South Wales, 300 km south-southwest of Sydney (Figure 3). The pluton is about 8 km in maximum dimension and has a surface exposure of 14–20 km^2, depending on where its gradational contact with the surrounding migmatites is placed (Johnson, Vernon, & Hobbs, 1994). When mapped, the pluton was found to be central to a sequence of roughly concentric prograde regional metamorphic zones (Browne, 1914; Joplin, 1942, 1962). In fact, the Cooma metamorphic complex is considered to be a classic geological area for regional metamorphic zones, because it is one of the first localities where andalusite-sillimanite type regional metamorphism was described (Joplin, 1942; Miyashiro, 1973). Furthermore, the Cooma granodiorite itself is also regarded as a classic geological example of a pluton produced by a low degree of partial melting of the metasediments at the heart of a regional metamorphic complex (Figure 3) (Hall, 1996).

The Cooma metamorphic complex has a mapped outcrop area exceeding 300 km^2, and probably extends over a similar area beneath the local cover of Tertiary basalt. Isograds can be traced over 30 km northwards adjacent to the Murrumbidgee Batholith (Richards, Collins, & Needham, 2000). Based mainly on the work of Joplin (1942, 1968) and Hopwood (1969, 1976), Chappell & White (1976) recognized a series of metamorphic zones delineated by the appearance of chlorite, biotite, andalusite, sillimanite, and granitic veining, respectively. Approximate equivalents are chlorite zone—greenschist facies; biotite and andalusite zones—amphibolite facies; sillimanite and migmatite zones—granulite facies (Chappell, White, & Williams, 1991). Some additional metamorphic zones have been distinguished by subdividing the andalusite and sillimanite zones on the basis of the first appearances of cordierite, andalusite and K-feldspar (Johnson et al., 1994). The zoning is markedly asymmetric. The belt of highest grade rocks and the enclosed Cooma granodiorite are located towards the eastern margin of the complex (Figure 3), with the regional aureole extending approximately 3 km to the east, but nearly 10 km to the west. At least four (Johnson, 1992), and possibly seven (Johnson et al.), separate deformation fabrics can be distinguished in the metasediments of the Cooma complex. The exception is the Cooma granodiorite, which preserves only the last foliation, suggesting that it was emplaced late in the development of the complex (Johnson, 1992, 1999).

The Cooma granodiorite contains the same minerals as the gneisses and migmatites and lies within the cordierite-andalusite-K-feldspar zone. It is extremely quartz-rich (50%) and contains plagioclase, K-feldspar and biotite, with andalusite, sillimanite,

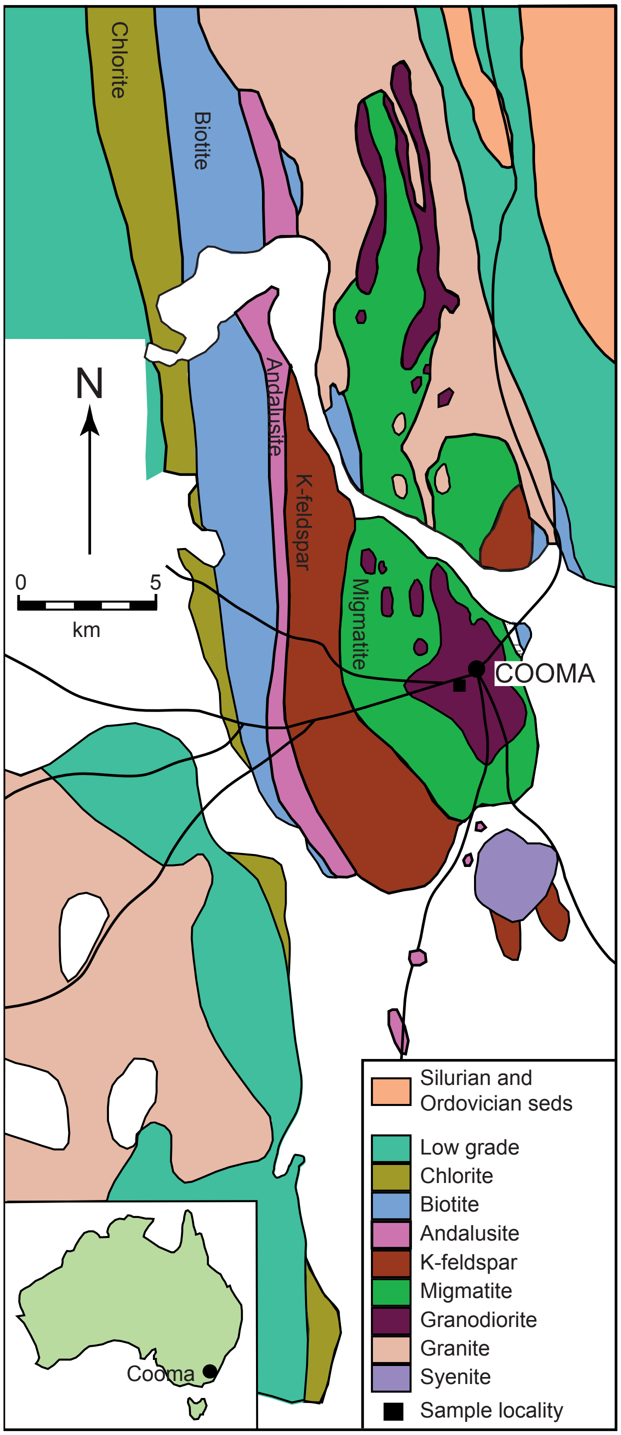

Figure 3. Geologic and location maps for the Cooma granodiorite and the surrounding regional metamorphic zones in southeastern Australia. The location of the sample used in this study is also shown.

cordierite, and muscovite, some or all of the latter appearing to be secondary (Chappell & White, 1976; Ellis & Obata, 1992; Joplin, 1942). The biotite is crowded with radiohalos around inclusions of zircon and monazite (Williams, 2001). The granodiorite contains abundant xenoliths of the surrounding migmatites and, less commonly, the high-grade gneisses, quartz veins and pegmatites, which is consistent with the granodiorite having been derived by partial melting of a metasedimentary source, presumably the high-grade gneisses surrounding the granodiorite (Johnson et al., 1994). Thus the granodiorite has been classified as S-type (Chappell & White, 1974), with normative corundum values of 5.82% (Chappell, White, & Williams, 1991), indicating that it is strongly peraluminous, and is very low in Na_2O and CaO, which has been attributed to its derivation from the surrounding metamorphosed Ca-poor Ordovician sediments (Chappell et al.). This origin is supported by isotopic data (Chappell et al; McCulloch & Chappell, 1982; Munksgaard, 1988; Pidgeon & Compston, 1965; Williams, 2001). The Cooma granodiorite is thus typical of "regional aureole" granites described by White, Chappell, & Cleary (1974) and Chappell & White (1976).

Radioisotopic data suggests that the Cooma granodiorite and the related metamorphic rocks thus cooled through the blocking temperature for most geochronological systems in the mid to late Silurian (Chappell et al., 1991). Pidgeon & Compston (1965) obtained an Rb-Sr mineral isochron age for the granodiorite of 406±12 Ma. The age of the high-grade gneisses was found to be similar to the granodiorite, but the low grade metasediments yielded a significantly older age of 450±11 Ma (recalculated by Munksgaard, 1988). Based on these results it was concluded that the granodiorite formed in situ by partial melting of the surrounding metasediments, the high-grade gneisses being associated with the emplacement of the granodiorite, whereas the higher ages in the low-grade metasediments perhaps indicated the original age of deposition or the age of regional metamorphism pre-dating the high-grade metamorphism. Tetley (1979) obtained a Rb-Sr whole-rock isochron age for the granodiorite of 410.0±19.0 Ma, thus supporting the previously determined granodiorite age. However, Munksgaard obtained whole-rock Rb-Sr ages of 362±77 Ma for the granodiorite, 375±55 Ma for the high-grade gneisses and 386±25 Ma for the low-grade metasediments, results which he suggested implied the metasediments and the granodiorite were not fully equilibrated on a regional scale with respect to their Sr isotope composition at the time of metamorphism, and thus whole-rock samples would not give meaningful ages for the Cooma complex. Nevertheless, he showed that the Cooma granodiorite is similar in major- and trace-element composition to a calculated mixture of the surrounding schists and gneisses.

Preliminary results of ion-probe zircon U-Pb studies (Chappell et al., 1991) yielded ages from zircon about 30 Ma greater than the 410 Ma age recorded by hornblende K-Ar and whole-rock Rb-Sr

(Tetley, 1979). More detailed results have now been published (Williams, 2001). Both monazite and zircon grains from the Cooma granodiorite and from the metasediments in each of the surrounding regional metamorphic zones were analyzed. Monazite in the migmatite and granodiorite were found to have recorded only metamorphism and granite genesis at 432.8±3.5 Ma, whereas detrital zircon grains in the original sediments were unaffected by metamorphism until the inception of partial melting, when platelets of new zircon precipitated on the surfaces of the grains. These new growths of zircon crystals, although maximum in the leucosome of the migmatites, was best dated in the granodiorite at 435.2±6.3 Ma. Thus the best combined estimate for the U-Pb age of the metamorphism and granite genesis is 433.4±3.1 Ma. However, detrital zircon U-Pb ages were found to have been preserved unmodified throughout metamorphism and magma genesis, which was concluded to indicate derivation of the Cooma granodiorite from lower Paleozoic source rocks with the same protolith as the Ordovician sediments found outcropping adjacent to the metamorphic complex in the same region. These U-Pb ages for the detrital zircon and monazite grains preserved in the metasediments and the granodiorite from the original Ordovician sediments were dominated by composite populations dated at 500–600 Ma and 900–1200 Ma, although almost 10% of the grains analyzed yielded apparent ages scattered from 1450 Ma to 2839 Ma, one grain even yielding an apparent age of 3538 Ma.

The general consensus is that the Cooma granodiorite is an integral part of the regional metamorphic sequence, having formed by the in situ, or virtually in situ, partial melting of high-grade metasediments identical to those surrounding it (Chappell et al., 1991; Ellis & Obata, 1992; Gray, 1984; Joplin, 1942, 1962; McCulloch & Chappell, 1982; Munksgaard, 1988; Pidgeon & Compston, 1965; White & Chappell, 1988; White et al., 1974). However, Flood & Vernon (1978) pointed out that an origin for the Cooma granodiorite from essentially in situ anatexis of the adjacent metasedimentary rocks was in apparent conflict with the surrounding low-pressure metamorphic environment, unless unrealistically high and localized geothermal gradients were invoked. They suggested that subsequent to the granodiorite forming by partial melting of the adjacent high-grade migmatitic rocks, the granodiorite moved upwards as a diapiric intrusion, the high-grade envelope surrounding it having been dragged up to higher crustal levels with the intruding granitic diapir. Support for this model includes evidence for vertical movement along a transition zone between the andalusite zone schists and the K-feldspar zone gneisses (Figure 3), a step in metamorphic pressures at the sillimanite isograd, coinciding with the boundary between the gneisses and migmatites, and a steady pressure rise thereafter towards higher metamorphic grades (Troitzsch, 1995). All the metamorphism is regarded as part of the same relatively intact sequence, the thermal aureole having contracted towards the granodiorite during the later stages of the deformation associated with the regional metamorphism and the emplacement of the granodiorite (Richards et al., 2000). Finally, Vernon, Richards, & Collins (2001) have demonstrated that in situ partial melting of metapsammitic leucosome would have produced a magma of suitable composition to form the Cooma granodiorite, but this locally produced magma appears to have only contributed to the rising pluton of magma formed by deeper, more extensive accumulation of similarly derived magma, a model consistent with the U-Pb zircon data (Williams, 2001).

Sampling and Laboratory Procedures

Each of these granitic plutons was sampled at the locations shown in Figures 1, 2, and 3. In most instances access was available by roads and samples were collected in roadcuts where the outcrops were freshest. Fist-sized (1–2 kg) pieces of granite were collected at each location, the details of which were recorded using a Garmin GPSII Plus hand-held unit.

A standard petrographic thin section was obtained for each sample. In the laboratory, a scalpel and tweezers were used to prise 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 scotch tape fixed to a bench surface with its adhesive side up. Once numerous biotite flakes had been mounted on the adhesive side of this piece of scotch tape, a fresh piece of scotch tape was placed over them and firmly pressed along its length so as to ensure the two pieces of scotch tape were stuck together with the biotite flakes firmly wedged between them. The upper piece of scotch tape was then peeled back in order to pull apart the sheets composing the biotite flakes, and this piece of scotch tape with thin biotite sheets adhering to it was then placed over a standard glass microscope slide so that the adhesive side and the thin mica flakes adhered to it. This procedure was repeated with another piece of 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 10–20) thin biotite flakes mounted on them. This is similar to the method pioneered by Gentry. A minimum of 30 microscope slides was prepared for each sample to ensure good representative sampling statistics.

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.

Results

All results are listed in Table 1. In the Stone Mountain monzogranite ^{210}Po radiohalos outnumbered all other radiohalo types. For the six samples 291 thin sections were scanned and yielded 1139 ^{210}Po radiohalos, 93 ^{214}Po halos, and 88 ^{238}U radiohalos, the average proportions being approximately 13 ^{210}Po radiohalos to every ^{214}Po and ^{238}U radiohalo, which occurred in approximately equal numbers. For the individual samples these proportions varied from a low of about six ^{210}Po radiohalos for every ^{214}Po radiohalo, to a high of 69 ^{210}Po halos for every ^{214}Po radiohalo. ^{238}U radiohalos were always found in similar numbers to the ^{214}Po radiohalos. Additionally, in sample SMG-5 two ^{218}Po radiohalos were found, while in sample SMG-2 where no ^{214}Po radiohalos were found, four of the ^{210}Po radiohalos were found in muscovite, an unusual but not unknown occurrence (Ramdohr, 1960).

A smaller number of radiohalos (437) were counted in 563 slides from twelve samples of the La Posta pluton. Indeed, radiohalos were relatively rare in the biotite flakes from the hornblende-biotite facies, large biotite facies, and small biotite facies zones of the pluton. Only the muscovite-biotite facies core of the pluton contained appreciable numbers of radiohalos, the proportions being 86 ^{210}Po radiohalos, three ^{214}Po radiohalos and one ^{238}U radiohalo in 180 slides from four samples. Of potential significance is the substantially voluminous occurrence of radiohalos in the genetically and spatially related Indian Hill and other monzogranite plutons, three samples yielding 279 ^{210}Po radiohalos, 11 ^{214}Po radiohalos and 45 ^{238}U radiohalos in 130 slides. This is a distribution of approximately 25 ^{210}Po radiohalos for every ^{214}Po and every four ^{238}U radiohalos. Thus ^{210}Po radiohalos are approximately as prolific in the Stone Mountain monzogranite as they are in the Indian Hill and other monzogranites, while the muscovite-biotite granodiorite core of the La Posta pluton has less than approximately one quarter of the number of radiohalos found in the genetically and spatially related Indian Hill and other monzogranites.

Table 1. Compilation of the Po, U, and Th radiohalos counted in samples from the three granitic plutons.

Pluton	Sample	Number of Slides	Radiohalos					Additional Notes (approximate proportional radiohalo numbers)
			^{210}Po	^{214}Po	^{218}Po	^{238}U	^{232}Th	
Stone Mountain	SMG-1	30	192	5	0	11	0	(38:5:0:2:0)
	SMG-2	30	90*	0	0	1	0	*4 in muscovite
	SMG-3	30	222	9	0	4	0	(49:2:0:1:0)
	SMG-4	30	138	2	0	1	0	
	SMG-5	30	179	36	2	26	0	(6:1:~0:1:0)
	SMG-6	141	288	41	0	45	0	(6:1:0:1:0)
La Posta	PRB-6	50	8	0	0	0	0	Hornblende-biotite facies
	PRB-7	50	2	0	0	0	0	Large biotite facies
	PRB-5	53	0	1	0	1	0	Small biotite facies
	PRB-22	50	0	0	0	0	0	
	PRB-4	50	36	0	0	6	0	Muscovite-biotite facies
	PRB-20	30	15	3	0	1	0	
	PRB-24	50	18	0	0	0	0	
	PRB-25	50	17	0	0	0	0	
	PRB-21	30	56	11	0	15	0	Indian Hill monzogranite
	PRB-23	50	159	0	0	0	0	Other monzogranite
	PRB-26	50	64	0	0	30	0	
	PRB-27	50	0	0	0	0	0	Pegmatite
Cooma	RLG-2	41	373	44	0	418	37	(9:1:0:10:1)

The single sample of the Cooma granodiorite yielded the largest numbers of radiohalos, as anticipated from the reported occurrence of radiohalos around zircon and monazite inclusions in the biotite of this granodiorite (Williams, 2001). However, unlike the Stone Mountain monzogranite, the La Posta granodiorite, the Indian Hill and other monzogranites, ^{238}U radiohalos are a little more prolific than ^{210}Po radiohalos, and ^{232}Th radiohalos are found around monazite radiocenters. In the 41 slides examined there were approximately nine ^{210}Po radiohalos to every one ^{214}Po radiohalo, every ten ^{238}U radiohalos and every one ^{232}Th radiohalo. So Po radiohalos are far more prolific in the Cooma granodiorite. The ratio ^{210}Po:^{214}Po of 9:1 in the Cooma granodiorite is similar to that in the Stone Mountain monzogranite, although there is an average of approximately four ^{210}Po radiohalos per slide in the six Stone Mountain monzogranite samples compared to nine ^{210}Po radiohalos per slide in the single sample of Cooma granodiorite. Similarly, for comparison, whereas there are only approximately three ^{238}U radiohalos in every ten slides of the Stone Mountain monzogranite, there are at least 100 ^{238}U radiohalos in every ten slides of the Cooma granodiorite.

Discussion

Flood Origin of these Granitic Plutons

It is arguably beyond dispute that these three granitic plutons were intruded as hot magmas during the Flood, and that therefore these radiohalos found in them formed subsequently, during the Flood and thereafter. Froede (1995) “believes that the Stone Mountain granitic magma formed as a result of the mixing of some remelted original primordial granite which melted surrounding rocks and sediments” and suggests “that possibly the source magma of Stone Mountain was derived from deep within the crust during the tectonic event identified as the Alleghenian Orogeny (a Flood generated orogenic event).” However, the only evidence presented for these claims is that “the Stone Mountain granite is compositionally different from all of the other granites in the area.” Nevertheless, Froede is convinced by the field evidence that the Stone Mountain monzogranite was intruded as a hot magma during the Flood and then cooled rapidly, as evidenced by the pluton’s mineralogical and compositional homogeneity and its uniform grain size. Indeed, experimental work has shown that plutonic rocks with crystal sizes similar to those found in the Stone Mountain pluton can be grown in a matter of days or weeks (Lofgren, 1980). Furthermore, there is field evidence of contact metamorphism and metasomatism (Grant, 1962, 1986), so there is agreement that the Stone Mountain pluton formed by the intrusion of a hot granitic magma. However, based on geochemical, mineralogical and structural evidence the source of this granitic magma is undoubtedly the nearby Lithonia Gneiss (Hermann, 1954; Whitney et al., 1976), which itself appears to be a product of the regional metamorphism of the host rocks to the pluton. Indeed, isotopic evidence suggests that the same regional metamorphic event responsible for the Lithonia Gneiss and the metasediments that host the pluton was also responsible for the partial melting of the Lithonia Gneiss itself, conventional K-Ar ages obtained from its micas being within the range of radioisotopic “ages” obtained for the Stone Mountain monzogranite (Atkins et al., 1980; Dallmeyer, 1978; Fairbairn et al., 1960; Pinson et al., 1957; Whitney et al.). This still leaves unanswered the question of when the precursor sediments were deposited, but U-Pb “ages” of about 480 Ma for zircon grains in the Lithonia Gneiss (Grunenfelder & Silver, 1958) probably indicate these are detrital zircon grains inherited from the original sediments, which were thus probably deposited early in the Flood. This is consistent with the time of deposition of the fossiliferous sediments now making up strata in the Appalachians, including these metasediments in the Piedmont of Georgia (Fisher, Pettijohn, Reed, & Weaver, 1970).

The rocks into which the plutons of the Peninsular Ranges Batholith, including the La Posta pluton, have intruded are metasedimentary units that include the pelitic and psammitic schists and gneisses of the roof pendant in the La Posta pluton into which the Indian Hill monzogranite pluton has intruded (Figure 2) (Walawender & Girty, 1991; Walawender et al., 1991). These metasedimentary rocks are part of the sandstone-shale belt of Gastil (1975), a flysch-type sequence which extends southward through Baja California and which in southern California was named the Julian Schist by Hudson (Hudson, 1922). While the relative age of the Julian Schist is poorly constrained, an ammonite imprint found on a piece of quartzite within the Julian Schist has been identified as Triassic (Hudson), and Upper Triassic mollusks are reported from part of the sandstone-shale belt in the northern part of the Peninsular Ranges Batholith (Todd, Erskine, & Morton, 1988). These fossils therefore attest to the sediment precursors of the pre-batholithic metasedimentary rocks having been deposited during the Flood. Evidence that the La Posta pluton was intruded as a hot granitic magma includes the narrow discontinuous border facies where the pluton cooled against the older granitic rocks it intruded, and the contact metamorphic effects on marbles in the metasedimentary roof pendant immediately adjacent to the pluton at Dos Cabezas (Clinkenbeard & Walawender, 1989). Thus the La Posta pluton was probably intruded into the metamorphosed Flood-deposited sediments towards the end of the Flood. Though much of this granitic magma was undoubtedly sourced from oceanic crust that was partially melted after being metamorphosed during subduction near the margin of the overlying North American continental crust, there is evidence of contamination of the ascending diapir with this older metasedimentary continental crust (inheritance of detrital zircon grains) to produce the S-type muscovite-biotite granodiorite core of the pluton (Walawender et al., 1990, 1991). This subduction would have been a part of the global tectonic movements late in the Flood, and the oceanic crust being subducted would likely have been new oceanic crust generated during the Flood (Austin et al., 1994), so both sources for the granitic magma that produced the La Posta pluton were formed and deposited during the Flood. Heat from the intrusion of the La Posta pluton appears to have been responsible for partial melting of the metasediments (Julian Schist) into which it was intruding, and this melt was first injected as pegmatites before the main body of granitic magma that had been generated intruded as the Indian Hill and the other garnetiferous muscovite-biotite monzogranite plutons (Figure 2) (Walawender & Girty, 1991, Walawender et al., 1991).

There is a strong general concensus based on overwhelming evidence that the source of the hot granitic magma that cooled to form the Cooma pluton was partial melting of the high-grade metamorphic gneisses and migmatites that are adjacent to the pluton (Johnson et al., 1994; Vernon et al., 2001; Williams, 2001). Indeed, the boundary of the granodiorite with the surrounding migmatites is gradational, and the granodiorite pluton is central to the metamorphic zones around it that therefore represent a regional aureole to the pluton. The metasediments can in turn be traced outwards from the pluton through the decreasing grade regional metamorphic zones to the adjacent original Ordivician sedimentary rocks, turbidites that are predominantly clay/quartz mixtures of shales and greywackes which elsewhere in the Lachlan Fold Belt contain an abundance of graptolite fossils (Fergusson & Fanning, 2002). Detrital zircon grains with inherited U-Pb ages, found in both the Cooma granodiorite and the surrounding metasediments from which it is derived (Williams), are similarly found in these fossiliferous Ordovician sediments elsewhere in the Lachlan Fold Belt (Fergusson & Fanning). Thus it is beyond dispute that these sediments, which were the source via partial melting of the Cooma granodiorite, were first deposited early during the Flood, and the granitic magma was intruded as a hot diapir at the heart of this regional metamorphic complex also during the Flood.

Implications

Having established that the granitic rocks of these three plutons were not only intruded as hot magmas and cooled during the Flood, but that the sources of these were Flood-deposited sediments and oceanic crust formed during the Flood (for much of the La Posta magma), the radiohalos found in the biotite grains within these granitic rocks need to be understood within the framework of the year-long Flood about 4,500 years ago. There are a number of immediate implications. First, the presence of so many dark, fully-formed (mature) ^{238}U radiohalos in these granitic rocks (and ^{232}Th radiohalos also in the Cooma granodiorite) indicates that at least 100 million years worth of radioactive decay at today's rates (Gentry, 1973, 1974; Humphreys, 2000; Snelling, 2000) has occurred in these granitic rocks since the biotites in them cooled sufficiently to record the α-decays from the parent ^{238}U (and ^{232}Th) in the tiny zircon (and monazite) inclusions in the biotites. Because these granitic rocks mostly formed from sediments deposited early in the Flood year, this implies that this would be a minimum estimate of the amount of radioactive decay that occurred during the Flood. Indeed, the La Posta pluton probably formed near the end of the Flood year, and yet the biotites in its granodiorite core and in its genetically and spatially related Indian Hill monzogranite pluton still record at least 100 million years worth of radioactive decay at today's rates. Thus these U and Th radiohalos are a physical, integral, historical record of at least 100 million years worth (at today's rates) of accelerated radioactive decay during the Flood and its accumulated rock record (Baumgardner, 2000; Humphreys; Snelling). This, in turn, implies that all conventional radioisotopic dating of these rocks, which relies on the assumption of constant decay rates, is grossly in error. Furthermore, the large pulse of heat flow generated by the accelerated decay would have helped to initiate and drive global tectonic processes during the Flood year and to accomplish catastrophically much geologic work, including regional metamorphism and anatexis of crustal and mantle rocks to produce granitic and other magmas.

Second, because the granitic rocks in these plutons are not primordial, that is, formed by fiat creation, the Po that parented the Po radiohalos found in the biotites in them cannot have been primordial either. Thus the hypothesis that the three different types of Po radiohalos found in biotites always represent the decay of primordial Po (original Po not derived by U-decay) (Gentry, 1979, 1980, 1982, 1983, 1984, 1986, 1988, 1993) has been falsified, as has the related hypothesis that any granitic rocks in which Po radiohalos are found must be primordial rocks produced by fiat creation. This is, to say the least, extremely disappointing, because so many young-earth creationists (the present authors included) have in the past often used the Po radiohalos as evidence of fiat creation of the rocks containing them. Nevertheless, the falsifying of this hypothesis does not in any way falsify the general creation hypothesis based on Scripture, that "in the beginning God created the heaven and the earth." But it does illustrate that the science built on that belief is subject to the normal rules of the scientific method, in particular, the making of predictions and the proposing of hypotheses that can be either verified or falsified. However, the presence of the Po radiohalos in these granitic rocks, which formed during the Flood by the cooling of hot magmas produced by the melting of Flood-deposited sediments, remains an enigma that still requires an explanation.

The Source of the U-Decay Products

The fact that the radiohalos are not homogeneously distributed in the La Posta pluton potentially provides another clue, for even though biotite is present throughout the pluton it is in the muscovite-biotite granodiorite core where most of the radiohalos are found. Indeed, the Stone Mountain monzogranite, the Indian Hill monzogranite and the Cooma granodiorite are all muscovite-biotite granitic rocks similar to the muscovite-boitite granodiorite in the core of the La Posta pluton, so this suggests that the mineral and chemical composition of the granitic rocks determines their radiohalo content. Obviously, U and Th must be present, concentrated in accessory minerals such as zircon and monazite within biotite flakes. The apparent correlation between the presence of muscovite and the radiohalos suggests that the source of the granitic magma, which then largely controls the composition of the granitic rock, is crucial. The common factor between all these muscovite-biotite granodiorites and monzogranites in these plutons is that their magmas were sourced in sedimentary rocks containing detrital zircon grains, sedimentary rocks that were first metamorphosed before anatexis extracted granitic magmas from them. These are then known as S-type granitic rocks, and the presence of muscovite in them is indicative of that classification. Furthermore, U-Pb isotopic data on zircons in these monzogranites and granodiorites confirms inheritance of zircons that were detrital grains in the original sediments. It is also significant that muscovite-biotite, or two-mica, granitic rocks often contain above average concentrations of U, and may even contain accessory uraninite (Ball, Bashan, & Michie, 1982; Rich, Holland, & Petersen, 1977). Indeed, two-mica granites are spatially and genetically associated with hydrothermal vein uranium deposits in western Europe and North America, the granitic rocks being favorable sources of leachable U by hydrothermal fluids in the late stages of the cooling of the plutons.

However, none of these granitic plutons (the Stone Mountain, La Posta, Indian Hill, and Cooma plutons) is known either for its accessory uraninite grains or for being associated with, or even hosting, hydrothermal vein uranium deposits. The only exception is a reference to the occurrence of a secondary uranium mineral, uranophane, associated with the Stone Mountain pluton (Watson, 1902). This indicates that there must have been leachable U in this pluton, which in this instance must have been dissolved and concentrated by, and precipitated from, supergene ground waters. So if U has been leached from the Stone Mountain pluton simply by oxidizing ground waters near the earth's surface, it is almost certain that more highly reactive hydrothermal fluids, produced both from the crystallizing and cooling magma and by the influx of water contained within the country rocks being intruded (Snelling & Woodmorappe, 1998), would have been even more capable of leaching and transporting U and its decay products through the monzogranite and its constituent minerals.

Now if these monzogranite and granodiorite plutons do not contain accessory U minerals, then what may have been the source of leachable U in them? Clearly, the answer is obvious, given that the ^{238}U radiohalos in the biotites of these granitic rocks all surround tiny inclusions of zircon. For example, in the Cooma granodiorite Williams (2001) found that the U content of the zircon grains ranged from 20 to 831 ppm, while the monazite grains ranged from 1281 to 7222 ppm U. However, of even greater significance to the present discussion is that Williams found that in the Cooma metamorphic complex the detrital monazite in the metasediments began to dissolve at lower amphibolite facies and virtually disappeared by upper amphibolite facies. At conditions above the upper amphibolite facies it began to regrow. Thus, whereas the detrital monazite U-Pb ages survived through to the mid-amphibolite facies, at higher grades the monazite grains only record the metamorphism and granite genesis. Similarly, while the detrital zircon was unaffected by metamorphism until the inception of partial melting when new zircon precipitated as overgrowths on the surfaces of the detrital grains, the U-Pb ages of these overgrowths record the metamorphism and granite genesis, in contrast to the preserved and modified detrital zircon U-Pb ages. Thus as a result of the dissolving of both monazite and zircon grains as the metamorphic grade increased towards partial melting and genesis of the granitic magma, U and its decay products would have been released into solution and were not all incorporated into the new growth of monazite and zircon, as evidenced by the resetting of the U-Pb ages. In particular, this implies that the U-decay products that had accumulated in the detrital zircons and monazites prior to the metamorphism and anatexis were not incorporated in the new growth of zircon and monazite, being therefore free to migrate dissolved in the hydrothermal fluids of the magma as it crystallized and cooled.

Similarly, the Stone Mountain monzogranite, the La Posta granodiorite core and the Indian Hill monzogranite all have evidence of inherited detrital zircon grains in which the U-Pb isotopic system was reset by metamorphism and anatexis of the source sediments. The U-decay products released from these zircons during magma genesis were thus separated from their parent U and free to migrate within the melt. Upon cooling and crystallization of the melt, the U-decay products would then migrate into the hydrothermal fluids also released by the cooling magma. Thus the available zircon U-Pb isotopic data for these granitic rocks (Clinkenbeard, 1987; Parrish, 1990; Walawender et al., 1990; Williams, 2001) provide unambiguous evidence of the isotopic separation of U-decay products, including Po isotopes, from their parent ^{238}U. These decay products were then available in large quantities within the zircon grains that had been incorporated into the S-type granitic rocks from their sediment precursors. This process thus eliminates one of the claimed formidable obstacles to any secondary transport of Po isotopes into radiocenters within biotite flakes to subsequently form the Po radiohalos (Gentry, 1973). This isotopic separation process has been demonstrated to occur naturally.

Hydrothermal Fluid Transport

Quite obviously none of the radiohalos could form until the biotite crystals had formed and cooled sufficiently to preserve the α-particle tracks (with no erasure by thermal annealing). The fact that Po (and also U and Th, of course) radiohalos are found in the biotites of these granitic rocks indicates that these radiohalos formed below the temperature at which radiohalos are thermally erased from biotite. The only available data suggests that thermal erasure of radiohalos in biotite occurs at and above 150°C (Armitage & Back, 1994; Laney & Laughlin, 1981). This temperature corresponds to that 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, when the water and volatiles held in solution in the magma are released (Burnham, 1997; Giggenbach, 1997). Of course, hydrothermal transport of U-decay products such as Ra, Rn, and Po would have all started as soon as hydrothermal fluids formed at temperatures above 150°C at which thermal erasure of α-tracks occurs. There would be no record of decay product passage at those elevated temperatures between or within mineral grains in the granitic rocks, because the α-tracks (and fission tracks, if U were also being transported) would be erased. Some time would thus elapse during pluton cooling for the dissolved isotopes to diffuse some distance in the flowing hydrothermal fluids and to become concentrated in new radiocenters without leaving any trace of their passage. The only stipulation demanded by the observable evidence is that by the time the temperature dropped below the radiohalo thermal erasure level (around 150°C in biotite) the species held in the new radiocenters must be only one of the three Po isotopes. There is no evidence of any other α-emitters in the Po radiohalos (Gentry, 1971, 1973).

It would thus seem plausible to postulate initial formation of the new radiocenters by transport of ^{226}Ra and/or ^{222}Rn, as their half-lives (1,622 years and 3.8 days respectively) allow more time for the transport process than the 3.1 minute half-life of ^{218}Po. This 3.1 minute half-life was initially regarded as an obstacle to any secondary transport process. Both Ra and Rn are readily soluble in water, with Rn primarily as a gas and Ra probably bonding with halides (Bagnall, 1957). However, Po is also readily transported in hydrothermal fluids as halide and sulfate complexes (Bagnall). Halide and sulfate species are common in hydrothermal fluids (Giggenbach, 1997). Not only is Rn a gas, but its diffusion coefficient of $0.985\,cm^2\,day^{-1}$ ($1.14\times10^{-5}\,cm^2\,sec^{-1}$) at a water temperature of only 18°C (Bagnall) is comparable with the diffusion coefficient for ^{218}Po of $7.9\times10^{-2}\,cm^2\,sec^{-1}$ in nitrogen gas at ambient temperatures with an 80% relative humidity (Frey, Hopke, & Stukel, 1981). By comparison, Pb has a diffusion coefficient within seven different minerals of $10^{-18}\,cm^2\,sec^{-1}$ (Gentry, 1975). Furthermore, biotite has a sheet structure with a perfect cleavage which preferentially and readily facilitates the passage of fluids through the mineral structure, in contrast to minerals that rarely contain radiohalos. Gentry et al. (1976) maintained that in minerals the diffusion coefficients are so low that there is a negligible probability for atoms of the Po isotopes to migrate even 1 μm through the mineral structures before decaying; but this argument would be irrelevant if the diffusion were occurring in hydrothermal fluids flowing along the cleavage planes in the biotite flakes.

However, Gentry (1989, 1998) has maintained that Po radiohalos do not occur along cracks or conduits in biotite, pointing to the 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.

In any case, how far do the hydrothermal fluids have to carry the ^{222}Rn and/or ^{218}Po? Because the source of these isotopes is the zircon crystals within the biotite flakes, and the resultant Po radiohalos are also in the same or adjacent biotite flakes (which is readily apparent from the microscope examination of normal rock thin sections where the total rock fabric is in view), the transport distances can be measured in the micron (µm) to millimeters (mm) range. These distances would easily be accomplished within the 3.8 day half-life of ^{222}Rn with its diffusion coefficient of $1.14\times10^{-5}\,cm^2\,sec^{-1}$ ($0.985\,cm^2\,day^{-1}$) in water at 18°C. The diffusion rate would be much faster in water at 150–200°C. By contrast, even though ^{218}Po has a similarly fast diffusion rate, because of the much shorter half-life of ^{218}Po (only 3.1 minutes) hydrothermal transport of ^{222}Rn would seem the most likely means of transporting the descendant Po isotopes to the new radiocenters. Brown (1997) favored ^{226}Ra to allow even more time for the required transport, 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 be reached in about 100 years after a zero-level starting point. However, we would consider that the timeframe for ^{226}Ra transport is longer than the timeframe allowable for the cooling of the granitic rocks from the temperatures at which the biotites crystallize (and include the zircon grains) and at which the hydrothermal fluids are exsolved, to the temperature at which α-tracks are thermally erased. All this cooling had to have occurred within much less than the year of the Flood, given that most, if not all, of the erosion that has exposed these plutons to the earth's surface occurred at the close of the Flood, only months after the intrusion and cooling of the granitic magmas earlier in the Flood year (probably only weeks earlier in the case of the La Posta and Indian Hill plutons). In our opinion, this restrictive timeframe would rule out ^{226}Ra (half-life 1,622 years) as the species transported in the hydrothermal fluids. Instead, the fast diffusion rate of gaseous ^{222}Rn (half-life 3.8 days) would appear to be adequate for a timeframe of only days for its transport by hydrothermal fluids while the granitic rocks were cooling through the temperatures of thermal erasure of α-tracks.

Supply of Sufficient Polonium

The next question to resolve is whether this proposed transport mechanism would supply enough ^{218}Po to the new radiocenters to subsequently produce the Po radiohalos? Gentry (1974) has calculated that the radiocenters of very dark ^{218}Po radiohalos, for example, may have needed to contain as much as 5×10^9 atoms (a concentration of more than 50%) of ^{218}Po, which he maintained needed to be in the radiocenters at the time of their formation to subsequently be successful in producing the ^{218}Po radiohalos. However, this calculation is based on fiat creation of the ^{218}Po as primordial within the radiocenters, a hypothesis that we have argued here from the observable data is falsified. On the other hand, the ^{222}Rn hydrothermal fluid transport model does not require 5×10^9 atoms of ^{218}Po to be delivered to each radiocenter all at the same time. Fluid flow could have progressively supplied this quantity over a period of days, the ^{218}Po atoms decaying at any given time in the radiocenter being replaced by more ^{218}Po atoms from the flowing hydrothermal fluids. All that is required is a steady hydrothermal fluid flow with a constant supply of Rn and Po, together with favorable conditions at deposition sites that became the radiocenters.

Given that some of the apparent U-Pb ages of the detrital zircons in these granitic plutons are extremely high, being equivalent to hundreds of millions of years worth of decay at today's rates, the implication is that the zircons also held within them relatively large concentrations of all the U-decay products in equilibrium at the time of metamorphism, anatexis, magma generation, and subsequent cooling. It has been calculated that in one gram of ^{238}U there are 2.53×10^{21} atoms. In radioactive equilibrium with its decay products, there would be associated 9.11×10^{14} atoms of ^{226}Ra, 5.8×10^9 atoms of ^{222}Rn, 3.22×10^6 atoms of ^{218}Po, less than 3 atoms of ^{214}Po, and 2.13×10^{11} atoms of ^{210}Po (Friedlander, Kennedy, & Miller, 1964). Thus, even when the zircon grains only have U concentrations of hundreds of ppm, the relative numbers of ^{222}Rn atoms would still be high and sufficient to deliver the needed concentrations of Po to the new radiocenters. This of course assumes that hundreds of millions of years worth of radioactive decay at today's rates had occurred in these zircon grains prior to the Flood, an assumption which is verified by the presence of mature U radiohalos in pre-Flood (Precambrian) granitic rocks (for example, Gentry, 1973, 1974, 1984, 1988; Henderson, 1934; Henderson & Turnbull, 1934; Holmes, 1931; Kerr-Lawson, 1927, 1928; Stark, 1936; Wiman, 1930; Wise, 1989). Thus a sufficient number of ^{222}Rn atoms would have been available to supply the new radiocenters with the needed concentrations of ^{218}Po atoms, perhaps even supplemented by hydrothermal fluid transport of some ^{218}Po atoms before they decayed. It would also seem possible that because of the even larger number of ^{210}Po atoms also available (2.13×10^{11} ^{210}Po atoms for every 2.53×10^{21} ^{238}U atoms) that some of these might also have been transported in the hydrothermal fluids, given the longer half-life of ^{210}Po (138 days compared with the 3.8 days of ^{222}Rn) and the probable similar diffusion rate. This concurrent hydrothermal fluid transport of ^{210}Po may be needed to explain the high numbers of observed ^{210}Po radiohalos in the biotites of these granitic rocks compared to the numbers of ^{214}Po radiohalos (ratios varying from about 6:1 to 69:1), which are usually similar to the numbers of ^{238}U radiohalos (except in the Cooma granodiorite). Such hydrothermal fluid transport of ^{210}Po has in fact been documented, with hydrothermal fluid transport of ^{210}Po having been measured over distances of up to several kilometers and transit times of 20–30 days (Hussain et al., 1995; Snelling, 2000).

Transport Timescale

In determining the timescale for the hydrothermal fluid transport of ^{222}Rn and for the establishment of new radiocenters for subsequent radiohalo development, the almost complete absence of ^{218}Po radiohalos in the biotites of these granitic rocks must be significant (only two ^{218}Po radiohalos have been observed in one of the Stone Mountain monzogranite samples). This would seem to indicate that while the other Po radiohalos were produced, there was insufficient time for the transport of sufficient U-decay products to establish significant new centers containing ^{218}Po atoms to produce ^{218}Po radiohalos. On the other hand, transport was slow enough for most ^{218}Po atoms to decay in transit before reaching the sites where ^{210}Po was redeposited.

It is also evident that the extremely short half-life of ^{214}Po (164 microseconds) gives it a lower probability of surviving transport than ^{210}Po has, so ^{214}Po radiohalos were not always formed compared with radiohalos from the longer-lived ^{210}Po atoms. Because the same pattern of six or more ^{210}Po radiohalos to every ^{214}Po radiohalo is found in almost every sample from these three granitic plutons (plus the subsidiary associated Indian Hill and other monzogranite plutons) there must be a common factor in operation that needs an explanation, such as the one given here. In other words, the pattern in the ratios of quantities of the different Po radiohalos evidently is directly related to the transport mode, distance and time. This observation supports the secondary transport model for the separation of the Po isotopes from their parent ^{238}U in the formation of the three discrete types of Po radiohalos.

Establishment of New Radiocenters

The final question that needs answering is how do the new radiocenters become established? Together with hydrothermal fluid transport, there needs to be a mechanism by which the Po isotopes are concentrated at particular locations that become discrete radiocenters. Transport may be as ^{222}Rn, but radon is an inert gas and has no chemical affinity with other species, so there is no chemical propensity for it to concentrate at discrete locations. Thus it would appear that the radiocenters could only have formed after the ^{222}Rn had decayed to ^{218}Po. This is consistent with only Po isotopes having been in the radiocenters, since only rings equivalent to α-emissions from the Po isotopes surround the radiocenters. Po behaves geochemically similar to Pb, with an affinity for S, Se, and halides, and even forms polonides with other metals (Bagnall, 1957). Gentry et al. (1976) have demonstrated that where Pb, S, and Se were available in coalified wood, Po transported through the coalified wood by fluids became attached to these species with which it has a chemical affinity, and became concentrated enough in radiocenters to produce ^{210}Po radiohalos.

Some biotites 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 (Ilton & Veblen, 1988). These tiny Cu inclusions were evidently deposited from Cu-bearing hydrothermal fluids that flowed along the cleavage planes within the biotite crystals. It is therefore reasonable to expect that the same hydrothermal fluids responsible for transporting Ra, Rn, and Po would have also transported metal and other ions, just as is observed (Giggenbach, 1997), and would thus have similarly deposited tiny inclusions of metals and other elements along the cleavage planes within biotites. Collins (1992) has correctly observed that the crystal lattice of biotite contains sites where negatively charged halide or hydroxyl ions can be accommodated. These lattice sites and other imperfections found along cleavage planes, being relatively large, would provide space for metal and other ions such as Po to enter and take up lattice positions or be concentrated at particular discrete places along the cleavage planes where the chemical environment was conducive. Collins also contended that the Po radiohalos formed as a result of the diffusion of ^{222}Rn in "ambient" fluids within the crystallizing granitic rocks. In this way Po was incorporated in discrete radiocenters along the cleavage planes in the biotite flakes where suitable ions had been concentrated in lattice sites and crystal imperfections, and where the chemical environment was conducive to Po being concentrated to form the discrete radiocenters. It needs to be emphasized again that all the Po atoms required to give the desired high concentration of Po in the radiocenters to produce the observed intensity of Po radiohalos do not have to be delivered by the fluid transport process at the same time. As Po atoms decayed further fluid flow delivered more Po atoms to the radiocenters, where the metal or other ions that had scavenged Po from the passing fluids had become free to scavenge more Po. Thus the required ring density is reached by accumulation over a period of time, during which fluid flow continues and supply of Po atoms is available.

Model Predictions and Implications

It needs to be stressed that this secondary transport model for the origin of the Po-rich radiocenters and therefore the Po radiohalos is tentative. Further data collection and analysis is needed. It is another hypothesis or model that is open to either verification or falsification. The strength and usefulness of this model can be tested by its ability to make predictions about future discoveries which can be tested. One predication that could be made is that Po radiohalos should be found not only in granitic plutons, but also in regional metamorphic rocks. It has been argued here that some granitic plutons containing Po radiohalos were derived from the regional metamorphic rocks adjacent to them, or associated with them; and 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 metasediments. Thus it is predicted that Po radiohalos should be found, along with U and Th radiohalos, in the metamorphic rocks that surround, and were the source of, the Cooma granodiorite. To have produced Po radiohalos the other required ingredient would have been the passage of hydrothermal fluids through the biotite crystals containing the tiny zircon and monazite inclusions. Thus the finding of Po radiohalos in these Cooma metamorphic rocks would also confirm the model for regional metamorphism in which hydrothermal fluids circulated and permeated through sediment layers of differing mineralogy and composition to facilitate the transformation of the precursor minerals to new metamorphic minerals now characteristic of each of the regional metamorphic zones we observe in metamorphic complexes today ((Snelling, 1994a, 1994b). The presence of U and Th radiohalos in metamorphic rocks has already been documented (for example, Nasdala, Wenzel, Andrut, Wirth, & Blaum, 2001; Rimsaite, 1967), and there is also some tentative documentation of Po radiohalos in high-grade metamorphic rocks (Wise, 1989). But concerted systematic observations now need to be made to verify the geological distribution and occurrence of all types of radiohalos in appropriate metamorphic rocks.

Verification of this hydrothermal fluid transport model for the secondary formation of Po radiohalos in both granitic and metamorphic rocks would have other far-reaching and powerful implications. Whereas it can be perceived as disappointing that the fiat creation hypothesis for the Po radiohalos and their host granitic rocks has been falsified, the timescale considerations in that hypothesis still remain. Any hydrothermal fluid transport model for the Po radiohalos must envisage extremely rapid flow of hydrothermal fluids, along with extremely rapid cooling of the granitic magmas and metamorphic rocks—cooling from the temperatures of their formation to below the temperature at which α-tracks are thermally erased. It is in that window of falling temperature that the fluid flow must occur to rapidly transport the Po isotopes and their precursors, and the α-tracks they make along their fluid flow paths must also be erased (Gentry, 1968). The short ^{222}Rn half-life requires this falling temperature window to be very short time-wise. And this implies very rapid cooling of the granitic magmas and the metamorphic rocks. The clear implication is that granitic plutons and metamorphic complexes that contain Po radiohalos had to have cooled very rapidly. The hydrothermal fluids that transported the Po isotope precursors also rapidly transferred the heat from the crystallizing and cooling granitic magmas, and away from the high grade metamorphic zones to the outer limits of the metamorphic complexes (Snelling, 1994a; Snelling & Woodmorappe, 1998). Thus it is contended that the presence of Po radiohalos in granitic and metamorphic rocks implies an extremely short timescale for the formation and cooling of these rocks (days, not weeks or years), a timescale consistent with the year of the catastrophic global Flood on a young earth.

Finally, because the Po radiohalos imply that rapid convective flows of hydrothermal fluids in granitic and metamorphic rocks rapidly cooled them, they also imply that these flows would have been responsible for the rapid deposition of metallic ore deposits (Barnes, 1997). This implication 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, and to massive sulfide deposits containing base and other metals. Deposit sizes from small to giant at many distinctive strata levels throughout the global geological record are included. Rather than disappointment and dismay at the failure of the hypothesis regarding the Po radiohalos as evidence for fiat creation, we have powerful far-reaching implications for the rapid formation of granitic and other plutonic rocks, regional metamorphic complexes, and metallic ore deposits on a global scale within the Flood year.

Conclusions

The discovery and documentation of the three types of Po radiohalos in the biotites within three granitic plutons that were clearly sourced and 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 U and Th radiohalos in the same biotites in these same granitic rocks may be considered physical evidence of at least 100 million years worth of radioactive decay at today's rates within a part of the Flood year. We consider this to be evidence of accelerated nuclear decay during the catastrophic Flood. Accordingly, conventional radioisotopic dating of rocks based on the assumption of constancy of decay rates is grossly in error. Furthermore, the heat generated by this accelerated nuclear decay would have contributed to catastrophic tectonic and geologic processes during the Flood.

Many related lines of evidence can be brought together in development of a viable hydrothermal fluid transport model for the precursors to the Po isotopes (principally ^{222}Rn), and probably also some Po atoms themselves. Sourced from zircon and monazite grains already included within biotite flakes, the hydrothermal fluids would have carried these isotopes only short distances along the cleavage planes of the same and adjacent biotite flakes to deposition sites where the chemical environment was suitable for concentration of the Po isotopes into radiocenters that then formed the Po radiohalos. The short half-lives of these isotopes require the hydrothermal fluid transport and chemical concentration timeframes to have been extremely short—less than in the order of ten Po half-lives. Furthermore, after Po atoms are deposited at radiohalo sites, the temperature must drop below the α-track annealing temperature before radiohalos can form. This implies that the timescale for cooling of the granitic plutons was also extremely short, measured in half-lives of these isotopes (days, not years).

The possibility of Po radiohalos, and thus also rapid hydrothermal fluid flows, in metamorphic rocks has powerful implications for the rapid formation and cooling of regional metamorphic complexes. This needs further investigation. Additionally, the Po radiohalo evidence for rapid hydrothermal fluid flow has far-reaching implications for the rapid deposition and formation of many classes of metallic ore deposits hosted by, and associated with, granitic, other plutonic, and metamorphic rocks. Thus the Po radiohalos are potentially powerful evidence for rapid geological processes within the year of the Flood on a young earth.

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