The Proceedings of the International Conference on Creationism

Volume 8
Print Reference: Pages 567-580

Article 47

2018

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Recommended Citation

Snelling, A.A. 2018. Radiohalos as an exploration pathfinder for granite-related hydrothermal ore veins: A case study in the New England Batholith, Eastern Australia. In Proceedings of the Eighth International Conference on Creationism, ed. J.H. Whitmore, pp. 567–580. Pittsburgh, Pennsylvania: Creation Science Fellowship.

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RADIOHALOS AS AN EXPLORATION PATHFINDER FOR GRANITE-RELATED HYDROTHERMAL ORE VEINS: A CASE STUDY IN THE NEW ENGLAND BATHOLITH, EASTERN AUSTRALIA

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ABSTRACT

It has been proposed that Po radiohalos were formed from Po derived by ^{238}U decay in the radiocenters of nearby ^{238}U radiohalos which was transported by hydrothermal fluids released from granite plutons as they cooled. Thus, since the same hydrothermal fluids have concentrated metals into economic ore veins in some granites, it has also been proposed Po radiohalos could potentially be used as an exploration pathfinder tool for discovering new ore veins associated with granites. This study in the New England Batholith, eastern Australia, found that Mole Granite samples proximal to known hydrothermal ore veins contained extremely high numbers of Po radiohalos, in contrast to a distant sample that contained almost 90% fewer Po radiohalos. However, in the Hillgrove Granite which also hosts hydrothermal ore veins, all samples contained moderate-high numbers of Po radiohalos similar to those in barren granite plutons elsewhere in the batholith. This is because the Hillgrove ore veins were not produced from the hydrothermal fluids expelled from that cooling pluton, but were precipitated from hydrothermal fluids as distant granitoid plutons cooled in a later magmatic event. Thus, the extremely high numbers of Po radiohalos in Mole Granite samples proximal to known ore veins successfully indicated their proximity to those ore veins. Therefore, Po radiohalos proved to be a reliable pathfinder for the hydrothermal ore veins. This strategy applied to the Stanthorpe Granite found two out of six samples with high to very high numbers Po radiohalos, potentially pinpointing areas for follow-up exploration for possible hydrothermal ore veins. Further detailed sampling work is recommended to develop this exploration tool. Nevertheless, since the same hydrothermal fluid flows responsible for the Po radiohalos were responsible for forming the ore veins, then the ore veins must have formed in the same very rapid timescale, within weeks, a timescale fully compatible with the biblical chronology of earth history.

KEY WORDS

radiohalos, granite plutons, hydrothermal fluids, ore veins, exploration pathfinder, New England Batholith, Hillgrove Granite, Mole Granite, Stanthorpe Granite

INTRODUCTION

Radiohalos are minute circular, colored or darkened, radiation-damaged areas in some minerals, resulting from α-emissions from central radioactive mineral inclusions (Gentry 1973, 1974). Often concentric darkened rings are distinguishable within the darkened circular areas. It has been demonstrated that the radii of these rings correspond to the energies of specific α-particles in the ^{238}U decay series and their travel ranges (Gentry 1984). Thus, a fully-developed ^{238}U radiohalo should have eight visible concentric rings which correspond to the eight α-decay steps in the ^{238}U decay series. It has also been determined that such a halo requires between 500 million and 1 billion α-decays to be fully-developed and darkened (Gentry 1988).

Among the variant radiohalos are many one, two and three ring halos whose rings correspond to the α-particles emitted by the three isotopes of polonium in the ^{238}U decay series – ^{210}Po, ^{214}Po, and ^{218}Po, respectively. This makes for a dilemma, because such halos were thus only parented by these three Po isotopes, yet they have half-lives of only 138 days, 164 microseconds, and 3.1 minutes, respectively. The realization that these Po radiohalos put apparently impossible time limits on the separation and transport of these Po isotopes to parent radiohalos independent of ^{238}U radiohalos led Gentry (1988) to suggest that the Po radiohalos were God's "fingerprints of creation," evidence that the host granites were apparently created by divine fiat.

Snelling (2000) reviewed the literature on radiohalos. He then recognized the spatial association of Po radiohalos to ^{238}U radiohalos meant that the Po which parented the adjacent Po radiohalos may have been derived from the ^{238}U decay products in the radiocenters of the ^{238}U radiohalos. He also observed that many radiohalo-hosting biotite flakes had been hydrothermally altered. Furthermore, many of the host granites had intruded into fossil-bearing sedimentary layers that therefore were deposited during the Flood, so the granites themselves had to form subsequently during the Flood and could thus not be creation rocks as postulated by Gentry (1988).

Consequently, Snelling and Armitage (2003) and Snelling (2005) proposed that hydrothermal fluids infiltrating along the cleavage planes within biotite flakes dissolved ^{226}Ra, ^{222}Rn and the Po isotopes emanating from ^{238}U decay within the zircon radiocenters of the ^{238}U radiohalos. At conducive sites down flow within the same biotite flakes the Po isotopes were deposited and concentrated in what became the radiocenters for ^{218}Po, ^{214}Po and ^{210}Po radiohalos as the Po isotopes decayed. Hydrothermal fluids are typically Cl-rich and are known to be capable of dissolving ^{226}Ra, ^{222}Rn and the Po isotopes, the latter particularly bonding with Cl (Snelling 2005). Hydrothermal fluids also carry S, and because Po behaves

geochemically the same as Pb it also bonds with S. Furthermore, the mica sheets making up the biotite structure are weakly bonded by K, OH, and F ions, so S and Cl ions can occasionally substitute at point loci within the cleavage planes. It was thus postulated by Snelling (2005) that as the hydrothermal fluids carrying ^{222}Rn and the Po along the cleavage planes between the biotite sheets, Po atoms were attracted to those point loci where they decayed, only to be replaced by more Po atoms attracted to the same S or Cl point loci. The Po radiocenters were thus formed surrounded by Po radiohalos.

Essential to this hydrothermal fluid model for the transport of the Po isotopes from the decay of ^{238}U in the radiocenters of ^{238}U radiohalos is the requirement of grossly accelerated ^{238}U decay (Vardiman et al. 2005). Several lines of evidence suggest that during the Flood when much of the fossil-bearing sedimentary rock record was accumulating, and when biotite-bearing granites were intruded into those sedimentary rocks, the decay rate of ^{238}U was grossly accelerated. Thus, whereas today's very slow ^{238}U decay rate produces only a few Ra, Rn and Po atoms very slowly, that grossly accelerated decay rate would have produced huge numbers of Ra, Rn and Po atoms very rapidly, which were then easily transported the short distances within the host biotite flakes to precipitate in the adjacent Po radiocenters and produce the Po radiohalos.

If the ^{238}U decay rate was accelerated by five orders of magnitude, as Vardiman et al. (2005) postulated, then it could be supposed the Po isotopes' decay rates were similarly accelerated, which could make their existence so fleeting there wouldn't be sufficient time for hydrothermal transport to form radiocenters. However, Vardiman et al. (2005) found that the amount of acceleration was related to the present half-lives of the parent radioisotopes, the slower the present decay rate resulting in the most acceleration. Thus, with such fast decay rates today, the Po isotopes' decay rates would virtually have not been accelerated. Furthermore, the accelerated decay rates would not have resulted in larger radii for ^{238}U radiohalos, as ring radii are not affected by the decay rates but are related to the energies of the emitted α-particles (Gentry 1973, 1974).

In this hydrothermal model, therefore, the Po accumulated in the radiocenters by time integration as Po was progressively deposited from the passing hydrothermal fluids (Snelling and Armitage 2003; Snelling 2005). So, instead of the Po radiohalos forming virtually instantaneously as proposed by Gentry (1988), the Po radiohalos formed over hours and days. This still has drastic time implications for the formation of granites. Whereas Gentry (1988) concluded that granites were created instantaneously by divine fiat, Snelling (2005, 2008a, 2014) postulated that granite magmas crystallized and cooled within days, which is still very radical compared to the uniformitarian timescale.

Subsequently, case studies were undertaken to test this hydrothermal fluid transport model for the formation of Po radiohalos. Most remarkable was the fulfilled prediction of many more Po radiohalos at the staurolite isograd in regionally metamorphosed sandstones in the Great Smoky Mountains, Tennessee-North Carolina, where the metamorphic reaction would have released a lot of water (Snelling 2008b). Then, in the Cooma regional metamorphic complex of southeastern Australia the numbers of Po radiohalos increased where water was released in the high-grade zone and in the central granodiorite, but decreased sharply in the zone of partial melting where water was dissolved into the melt, just as expected in the model (Snelling 2008c).

In granites, increased numbers of Po radiohalos were also found where they were predicted to be based on the release of hydrothermal fluids during granite crystallization and cooling. In the Shap Granite of northern England, prolific Po radiohalos matched the higher volume of hydrothermal fluids associated with that granite's large K-feldspar phenocrysts (Snelling 2008d). The nested plutons of the Tuolumne Intrusive Suite, Yosemite, California contain increasing numbers of Po radiohalos proportional to the increased volumes of active hydrothermal fluids within the sequentially emplaced intrusions (Snelling and Gates 2009). High numbers of Po radiohalos and active hydrothermal fluids coincide with the large K-feldspar phenocrysts in the second to last pluton and the connection to explosive volcanism of the last pluton. The Bathurst Batholith west of Sydney, Australia, consists of an enormous pluton (the Bathurst Granite) intruded into fossiliferous sedimentary strata and numerous smaller related satellite plutons and dikes, which field and textural data have established were sequentially intruded while still hot (Snelling 2014). The presence of Po radiohalos in all three sequentially-intruded granite phases is evidence that all this intrusive activity, and the cooling of all three granite phases, must have occurred within a week or two so that these Po radiohalos in them formed subsequently within days to weeks.

Initial studies had suggested that more Po radiohalos may be present in granites hosting hydrothermal ore veins, for example, the Land's End Granite, Cornwall, England, which hosts Sn ore veins (Snelling 2005). It was argued that if the proposed model for the formation of Po radiohalos was correct, then the same hydrothermal fluids responsible for transporting the Po within biotite grains within granites to form Po radiohalos may also have transported other metals. Such hydrothermal fluids are released late in the cooling of granite plutons and have concentrated within them metals of economic significance (Sn, W, Mo, Au, Ag, Cu, Pb, Zn, Sb) which do not substitute in the crystal lattices of granite-forming minerals. These metals subsequently end up being deposited by the hydrothermal fluids as economic ore veins in fractures within the granites and the surrounding host rocks. It was thus suggested that appropriate studies needed to be undertaken to confirm the possibility of Po radiohalos being an exploration pathfinder 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. The New England Batholith of eastern Australia was chosen to test this hypothesis.

THE NEW ENGLAND BATHOLITH

The New England Batholith of eastern Australia is composed of more than one hundred individual granite plutons (Fig. 1) (Shaw and Flood 1981). With an outcrop area of 15,000 km^2, it is one of the largest batholiths in eastern Australia. Conventionally dated as Upper Carboniferous (Pennsylvanian) to Triassic, the batholith is composed of 80% adamellite (quartz-rich granites with sub-

equal amounts of plagioclase and K-feldspar), 18% granodiorite, 1% diorite, 1% quartz-bearing monzonite, and <0.2% gabbro. The plutons have been grouped into five or six suites based on their geochemical, mineralogical and isotopic characteristics, and their claimed emplacement ages (O'Neil et al. 1977; Hensel et al. 1985). Two of these suites have S-type characteristics (that is, sedimentary protoliths), the Hillgrove and Bundarra Suites (Fig. 1), whereas the remainder are I-type (that is, igneous protoliths), the Moonbi, Uralla and Clarence River Suites. Leucoadamellite plutons that have been difficult to classify are grouped separately.

The country rocks into which the New England Batholith was intruded are part of the New England Fold Belt (Leitch 1975). The sedimentary and metasedimentary rocks are divided into western and eastern sequences separated by a major fault zone. The 12-13 km thick western sequence consists of gently-folded, fossiliferous Devonian-early Permian volcanogenic shales, mudstones, limestones, sandstones, and greywackes with occasional cherts, conglomerates and interbedded lavas (Packham 1969). The eastern sequence consists of similar age but strongly deformed, tightly-folded and regionally metamorphosed, volcanogenic greywackes, siltstones and mudstones, interbedded with locally abundant basaltic lavas and cherts.

Most of the plutons in the New England Batholith are barren of any economic metal deposits. However, several host, or are related to, hydrothermal ore veins of economic significance. The Hillgrove Granite (Fig. 1) hosts Au-Sb-W ore veins which have been discontinuously exploited since 1857 (Ashley and Craw 2004). Similarly, the Mole Granite (Fig. 1) hosts the Torrington Sn-W-topaz ore veins which have been exploited since 1881 (Audétat et al. 2000a, b).

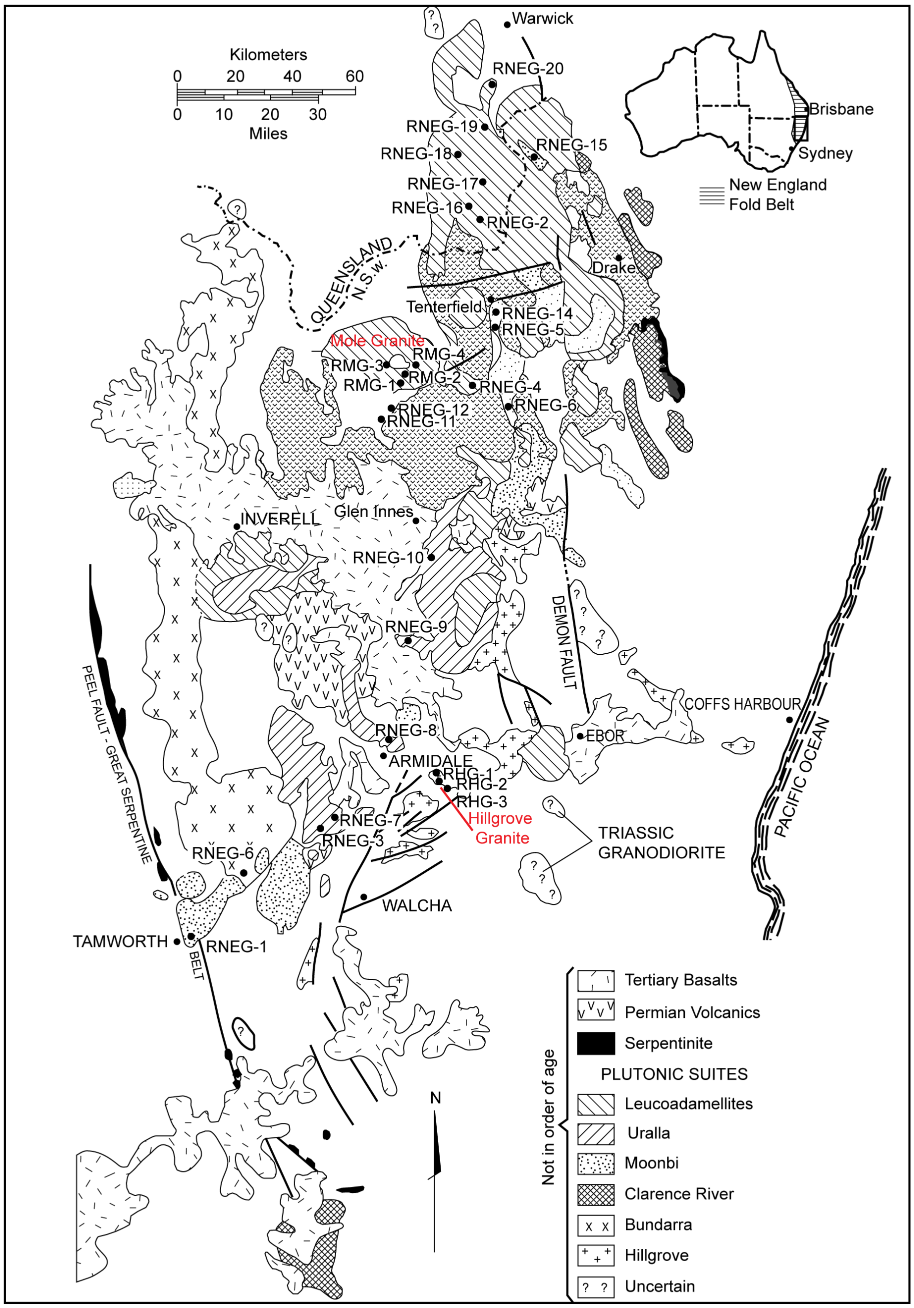

Figure 1. The distribution of the granite plutons, plutonic suites and leucoadamellites in the New England Batholith, eastern Australia (after Shaw and Flood 1981). The sampled plutons are indicated with the respective sample numbers.

THE HILLGROVE GRANITE AND ITS HYDROTHERMAL ORE VEINS

Au-Sb-W mineralization in the Hillgrove area occurs in veins, breccias and the immediately adjacent altered wall rocks (Ashley and Craw 2004). It is hosted by the deformed Paleozoic metasedimentary Girrakool Beds, and the late Carboniferous (~300 Ma) Hillgrove Granite, an S-type adamellite (or monzogranite as strictly defined), of the Hillgrove Plutonic Suite and the early Permian Bakers Creek Diorite Complex which intruded them (Fig. 2). The mineralized structures are commonly associated with lamprophyre dikes (Ashley et al. 1994).

The Girrakool Beds are possibly Carboniferous and comprise quartzofeldspathic greywacke, siltstone and siliceous (cherty) shale with a felsic volcaniclastic provenance. After their deposition, these rocks were strongly deformed, folded and metamorphosed to low grade, resulting in generally steeply-dipping beds and a strong cleavage parallel to the axial surfaces of meter-scale folds.

The Hillgrove Plutonic Suite (Fig. 1) was then emplaced into the Girrakool Beds in the late Carboniferous. The major pluton of the suite is the Hillgrove Adamellite, a massive to foliated S-type biotite monzogranite, locally with megacrystic K-feldspar, and accompanied by related feldspar-quartz porphyry dikes. Intrusive contacts with the enclosing metasedimentary rocks are sharp and commonly undeformed. However, contact metamorphic effects are apparent in the host metasedimentary rocks up to several hundred meters from the intrusion and

have resulted in development of assemblages of quartz, feldspars, and biotite ± aluminosilicates, muscovite, garnet and amphibole.

Heterogeneous deformation was subsequently imposed on both the metasedimentary rocks and granitoids, resulting in variably developed foliation and formation of steeply-dipping mylonite zones up to several hundred meters wide.

There are two main mylonite zones in the Hillgrove area, termed the Hillgrove Fault and Chandler Fault (Fig. 2), but other narrower zones are recognized.

Intrusion of the Bakers Creek Diorite Complex into the Girrakool Beds was approximately coeval with the emplacement of the Hillgrove Adamellite. The complex contains plutons with a range of compositions from quartz diorite to granodiorite. Contacts between the Bakers Creek Diorite Complex and the host metasedimentary rocks range from sharp to intercalated.

A subsequent deformation event was accompanied by regional prehnite-pumpellyite to greenschist facies metamorphism. This was followed by the emplacement of several suites of late Permian to early Triassic (~240-255 Ma) I-type granitoids (Shaw and Flood 1981).

Generation of several clusters of gold deposits coincided temporally with this latter deformation and magmatic episode. These hydrothermal systems range from Au-only to Sb-rich, commonly with significant As and locally associated W or Hg (Ashley and Craw 2004). In the Hillgrove area (Fig. 2), the hydrothermal ore veins transect the Hillgrove Adamellite and Bakers Creek Diorite Complex and developed coevally with the emplacement of shoshonitic lamprophyre dikes which commonly occupy the same structures. The lamprophyres have geochemical and temporal affinities (~245-255 Ma) with mafic granitoid (monzonite) members of the high-K Moonbi Plutonic Suite, the nearest intrusions of which though crop out about 15 km from Hillgrove.

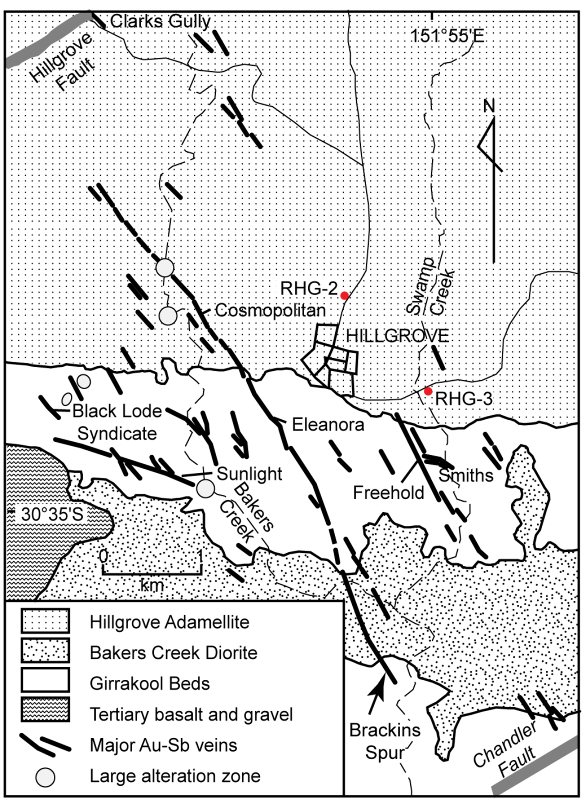

Figure 2. Geological map of the Hillgrove district (marked in Fig. 1) showing the location of the major Au-Sb vein systems and large hydrothermal alteration zones (after Ashley and Craw 2004). The sampled locations are indicated with the respective sample numbers.

The Hillgrove area contains over 200 individual ore deposits (Fig. 2), most of which comprise steeply-dipping mineralized veins within fracture systems cross-cutting the Hillgrove Adamellite, Bakers Creek Diorite Complex and the metasedimentary rocks which host them (Ashley and Craw 2004). The largest individual vein systems are up to 1.3 km long, up to several meters wide, and extend to a depth of at least 900 meters. Veins pinch and swell, with high-grade ore shoots commonly occupying dilational structures, which occur at various scales forming pipe- and lens-shaped hydrothermal breccia masses (altered angular wall-rock clasts cemented by hydrothermal minerals).

Individual veins and breccia masses show evidence of multiple generations of mineral precipitation, commonly with late, open-space infillings of quartz, stibnite (Sb_2S_3) and carbonate. Wall-rock alteration occurs in all host rock types and the lamprophyre dikes, and consists of distal chlorite-ankerite-albite and proximal ankerite-sericite-quartz-pyrite-arsenopyrite-rutile assemblages (Ashley et al. 1994). Uncorrected fluid inclusion filling temperatures in quartz from pyrite-arsenopyrite-gold mineralization zones range from 195 to 250°C, and for stibnite-gold-bearing veins from 100 to 195°C (Comsti and Taylor 1984). Low-salinity hydrothermal fluids (4.8 to 1.8 wt.% NaCl equivalent) are inferred for the mineralization.

THE MOLE GRANITE AND ITS HYDROTHERMAL ORE VEINS

The Mole Granite is one of the large leucoadamellite plutons in the northern New England Batholith (Fig. 1). It was intruded into Permo-Carboniferous sediments and Permian volcanics and has an outcrop area of 650 km^2 (Kleeman et al. 1997). The granite has several roof pendants, the largest of which is the metapelitic Torrington roof pendant, the altitude and central location of which in the Mole Granite suggests the granite roof collapsed (Fig. 3). Due to the roof of the pluton dipping shallowly outward at 7-15° it has been estimated that the pluton is only partially unroofed, and that there is another 1200 km^2 of the pluton still buried under the surrounding host sediments and volcanics. It has also been estimated that the pluton was emplaced at a depth of about 4 km, the inferred lithostatic pressure at that depth being consistent with the pressure established on coexisting brine and vapor inclusions in one of the mineralized lodes (Audétat et al. 2000b). The intrusion has been dated by conventional U-Pb techniques on magmatic zircon and monazite at 247.6 Ma (earliest Triassic) (Schaltegger et al. 2000). It produced a thermal metamorphic aureole up to 10 km wide.

Gravity-modeling and heat-flow measurements indicate the Mole Granite forms a sill-like mass 1-4 km thick (Audétat et al. 2000b). The exposed part of the intrusion is very homogenous in its mineralogy and geochemistry, suggesting that most of the magma intruded in

a single event. However, the Mole Granite is composed of three textural variants, which are (in decreasing order of abundance): seriate granite (the sizes of the grains range gradually down to the size of the groundmass grains); porphyritic granite (containing phenocrysts of quartz, K-feldspar, plagioclase and biotite in a fine-grained matrix of the same minerals); and microgranite (Audétat et al. 2000b; Kleeman et al. 1997). The porphyritic granite forms a 10-100-meter-thick layer in the apical portions of the intrusion. Primary topaz is a characteristic accessory mineral. In contrast, the seriate granite contains the same phenocryst assemblage, but has a coarser-grained matrix and does not contain any primary topaz. The contact between the porphyritic and seriate granite can be either sharp or gradual over a few meters. The microgranite is clearly the youngest phase, occurring as dikes and irregular masses within both other textural variants. Microgranite dikes follow the same fracture sets that control the hydrothermal quartz veins. Magmatic topaz is abundant in the microgranite dikes and can make up to several percent of the total rock volume.

More than 1200 hydrothermal ore vein deposits are recorded in the Mole Granite district, most of which have been mined for either Sn or W + Bi, and a smaller number for Cu, Pb, As, Zn, Ag, or Au (Audétat et al. 2000a, b) (Fig. 3). Except for some large, mineralized fault systems, all ore deposits are confined within the granite or to within 100-200-meters vertical distance from the granite contact with the surrounding host rocks. This hydrothermal mineralization within the granite occurs mostly in quartz veins, or as disseminations in massive quartz ± topaz greisens at the granite margin. Ore deposits outside the granite in the metamorphic aureole in the surrounding host rocks include pegmatites, sheeted veins (above ridges or cupolas in the granite intrusion roof), and mineralized faults and shear zones.

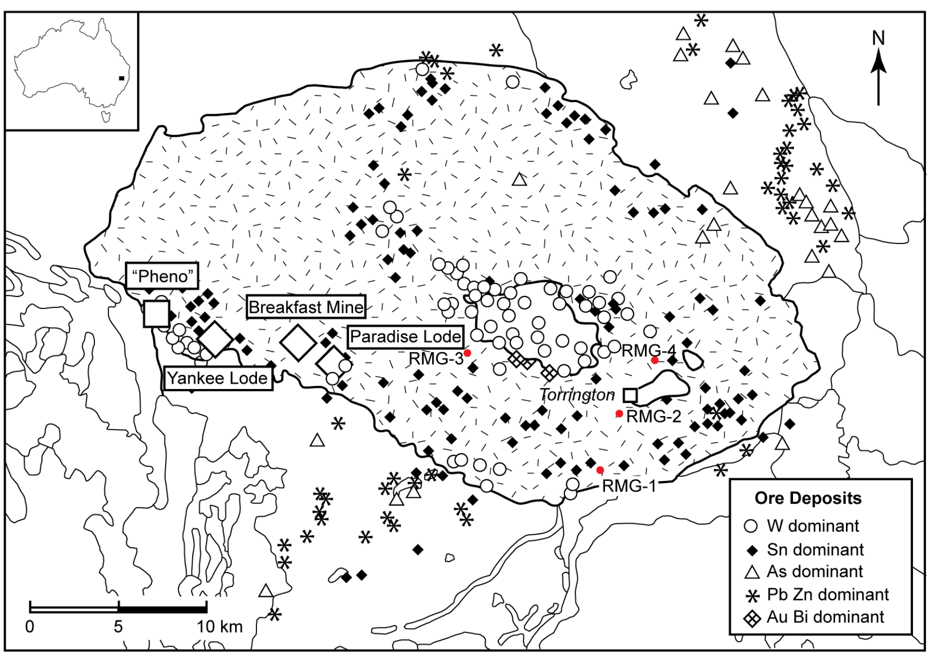

Figure 3. Outline of the Mole Granite (location marked in Fig. 1) with the distribution of hydrothermal ore deposits and the zonation of their metal content (after Kleeman et al. 1997; Audétat et al. 2000b). The W-dominated deposits occur preferentially at the granite margin, whereas the Sn-dominated deposits typically occur in the more deeply eroded parts of the intrusion. The sampled locations are indicated with the respective sample numbers.

After emplacement of the Mole Granite mass, steeply-dipping sheeted-vein systems comprise the earliest mineralization event, occurring in the metamorphic aureole in the host sedimentary rocks distal from the granite (Kleeman et al. 1997). The vein density increases towards the focus of the sheeted-vein systems, where up to 150 veins per linear meter occur, and vein systems decrease in width, vein density and vein width towards the granite. Individual veins are 0.1-3 centimeters wide. Quartz predominates in the veins with variable amounts of cassiterite (SnO_2), various Fe, As, Pb, Zn, Ag and Cu sulfides, tourmaline, topaz, muscovite, calcite and stilbite. Mineral assemblages in the veins are weakly zoned from Sn-As-Cu near the granite to Cu-As, As-Pb-Zn and Pb-Zn-Ag with increasing distance from the granite. Quartz from sheeted-vein systems has fluid-inclusion homogenization temperatures of 280-420°C, salinities of 20-40 equivalent wt.% NaCl and $\delta^{18}O$ of +7.5 to +9.5 ‰ (Plimer et al. 1995).

Rare pegmatites are present in the thermal metamorphic aureole and in the Torrington roof pendant (Kleeman et al. 1997). They may transgress sheeted-vein systems, or themselves be transgressed by microgranite, which demonstrates the earliest mineralization event was coeval with the waning stages of the granite intrusion. Pegmatites are typically 10-100 centimeters wide and have a great diversity of mineral assemblages. In most of them, the primary magmatic mineral assemblage comprises perthite-quartz-muscovite-albite-beryl, which has been partially replaced by Li-biotite, topaz, tourmaline, fluorite, muscovite, arsenopyrite, cassiterite and kaolinite. In one instance, a complex pegmatite also contains bismuth, various Bi, Cu, Pb, Zn, Co, Fe Ni, As, Sb sulfides, wolframite ([Fe, Mn] WO_4) and uraninite (UO_2). Fluid inclusions in quartz and beryl show evidence of boiling, have homogenization temperatures of 510-580°C, a salinity of 50-60 equivalent wt.% salts, and $\delta^{18}O$ of +9 to +10 ‰, which are in accord with a magmatic origin (Plimer et al. 1995).

Large multi-stage veins in the uppermost 100 meters of the seriate granite are controlled by joints, faults, shears and the walls of microgranite dikes (Kleeman et al. 1997). Fault- and shear-zone-hosted deposits are multiply veined and brecciated. Joint-controlled deposits are zoned with an innermost zone comprising quartz crystals covered with sulfides, and an outer zone comprising quartz crystals, chlorite books, and tabular wolframite. In places, the quartz crystals are pseudomorphed by cassiterite. Quartz from large veins has fluid inclusions with a great range of homogenization temperatures (220-350°C), salinity of 28-32 wt.% salts, and $\delta^{18}O$ of -4.4 to -13.8 ‰, interpreted as derived from a meteoric fluid circulating into the granite (Audétat et al. 2000a; Plimer et al. 1995).

There is a prominent metal zonation from Sn-dominated deposits (± B, Cu, Pb, Zn) within the granite, through W-dominated deposits (± F, Be, Bi, As, Mo) at the granite margin, to

sulfide-rich polymetallic deposits (As, Pb, Zn, Cu, Sb, Ag) in the surrounding sediments (Audétat et al. 2000a) (Fig. 3). This appears to reflect both a compositional variation of the source fluid, as well as sequential metal precipitation from it, because the pre-mineralization fluids in pure Sn and pure W deposits contain much higher amounts of base metals than Sn and W. Ore precipitation was probably driven by mixing of the magmatic and meteoric fluids in both types of deposits, as indicated by the local occurrence of extremely rich ore grades at the intersections of two vein systems, and by the general lack of correlation between the degree of wall-rock alteration and ore grade.

Thus, the most likely model for forming the mineralized veins is for fractures to start developing in the porphyritic granite margin of the intrusion as it cooled after its crystallization (Audétat et al. 2000a). Brine and vapor exsolved from the crystallizing melt below rose along these fractures and mixed with preheated meteoric water circulating in the upper parts of the granite. The relatively high temperature of the meteoric fluid (probably >300°C) explains why only Sn and W but little or no base metals were precipitated at the sites of fluid mixing. Further ascent of the fluid mixture into the colder country rocks led to a significant amount of cooling, which resulted in the precipitation of base metals in the upper parts of the vein systems. Throughout this process, brine-vapor separation caused selective enrichment of Cu, B, Li, As (± S, Ag, La) in the magmatic vapor phase, which condensed into the low-salinity meteoric fluid circulating in the upper parts of the granite.

Conventional U-Pb dating of hydrothermal xenotime and monazite in mineralized veins at 246.2 Ma and 244.4 Ma respectively (Schaltegger et al. 2000) is consistent with this model of the mineralization being deposited from hydrothermal fluids produced by magmatic fluids which were expelled from the crystalizing granite mixed with meteoric waters percolating into the granite from the host sedimentary rocks.

Figure 4. Typical outcrops of granite plutons in the New England Batholith (eastern Australia) that were sampled: **(A)** Sandy Flat Adamellite (sample RNEG-5); **(B)** Bendemer Adamellite (sample RNEG-6); **(C)** Shannonvale Granodiorite (sample RNEG-10); **(D)** Hillgrove Granite (sample RHG-3); **(E)** Mole Granite (sample RMG-1); **(F)** Mole Granite (sample RMG-3). Location details are in Figs. 1-3 and Table 1.

SAMPLE COLLECTION AND PROCESSING

A reconnaissance survey of various granite plutons in the New England Batholith, including the Hillgrove and Mole Granites, was undertaken and numerous samples collected. The sample collection sites are shown in Figs. 1-3. Examples of some of the outcrops sampled are shown in Fig. 4. The sample sites included exposed areas of the Hillgrove and Mole Granites both close to, and distant from, known ore veins. Access was via the New England Highway, secondary paved roads, and "bush" roads. Samples were removed by hammer from the outcrops, and labelled and sealed in plastic bags for transport to the laboratory. Locations were recorded using a hand-held GPS unit.

In the laboratory, the samples were thin-sectioned, and portions crushed to liberate their biotite grains. Biotite flakes were then peeled apart and mounted on microscope slides using Scotch™ tape, as per the technique described by Snelling (2005). Generally, fifty (50) slides each containing at least twenty (20) biotite flakes were prepared from each granite sample. This procedure enabled reasonable statistical comparisons between samples and between plutons, as approximately 1,000 biotite flakes were mounted for each sample and the radiohalos counted. The microscope slides for each sample were visually scanned systematically under a petrological microscope. All radiohalos were identified and their numbers tabulated.

RESULTS

Examples of the mineralogies and textures of these New England Batholith granites as examined under the microscope, including the Hillgrove and Mole Granites, are in Fig. 5. The radiohalos counts for each sample are listed in Table 1, which are grouped according to each pluton that was sampled. Examples of some of the radiohalos are in the photomicrographs in Fig. 6.

Most of the samples from these granite plutons contained low to moderate (0-250) total numbers of Po radiohalos. Total Po radiohalos numbers range from none in the Tent Hill Porphyrite (sample RNEG-11), likely due to it being very fine-grained, to 243 in the Sandy Flat Adamellite (sample RNEG-5). In the 18 samples in this 0-250 range in total Po radiohalos numbers the average is 113, which is the number in the Kingsgate Granite (sample RNEG-13). Those samples with higher (>250) total Po radiohalos numbers include one sample from the Uralla Granodiorite (sample RNEG-3 with 427), the Mt. Duval Adamellite sample (RNEG-8 with 335), and two samples from the Stanthorpe Adamellite (RNEG-2 with 540 and RNEG-17 with 382).

Most of these granite pluton samples contain only ^{210}Po radiohalos. The exceptions are the Moonbi Adamellite sample (RNEG-1 with 2 ^{218}Po radiohalos), the one sample of the Uralla Granodiorite which also had high ^{210}Po radiohalo numbers (RNEG-3 with 6 ^{218}Po radiohalos), and one of the two samples of the Stanthorpe Adamellite with high ^{210}Po radiohalo numbers (RNEG-2 with 5 ^{214}Po radiohalos and 15 ^{218}Po radiohalos).

All samples of these granite plutons contained low (<100) numbers of ^{238}U radiohalos, ranging from none in the Tent Hill Porphyrite (sample RNEG-11) to 76 in the same sample of the Uralla Granodiorite (RNEG-3) with the high numbers of ^{210}Po radiohalos (421) and ^{218}Po radiohalos (6). Even the two samples from the Stanthorpe Adamellite with high ^{210}Po radiohalo numbers (RNEG-2 with 520 and RNEG-17 with 382) had modest numbers of ^{238}U radiohalos (68 and 45 respectively). The only pluton containing a higher (but moderate) number of ^{238}U radiohalos is the Mt. Duval Adamellite (sample RNEG-8 with 167), which also has a high number of ^{210}Po radiohalos (335). Interestingly, the same sample of the Stanthorpe Adamellite which contained the high number of ^{210}Po radiohalos (520), but a low number of ^{238}U radiohalos (68) was the only sample to contain ^{232}Th radiohalos (19).

The three samples of the Hillgrove Granite all contained high total numbers of Po radiohalos (247-320), and very high numbers of ^{238}U radiohalos (346-391), while two samples each contained four (4) ^{214}Po radiohalos. Yet one of the samples (RHG-1) was distal to the ore veins (see Fig. 2). These

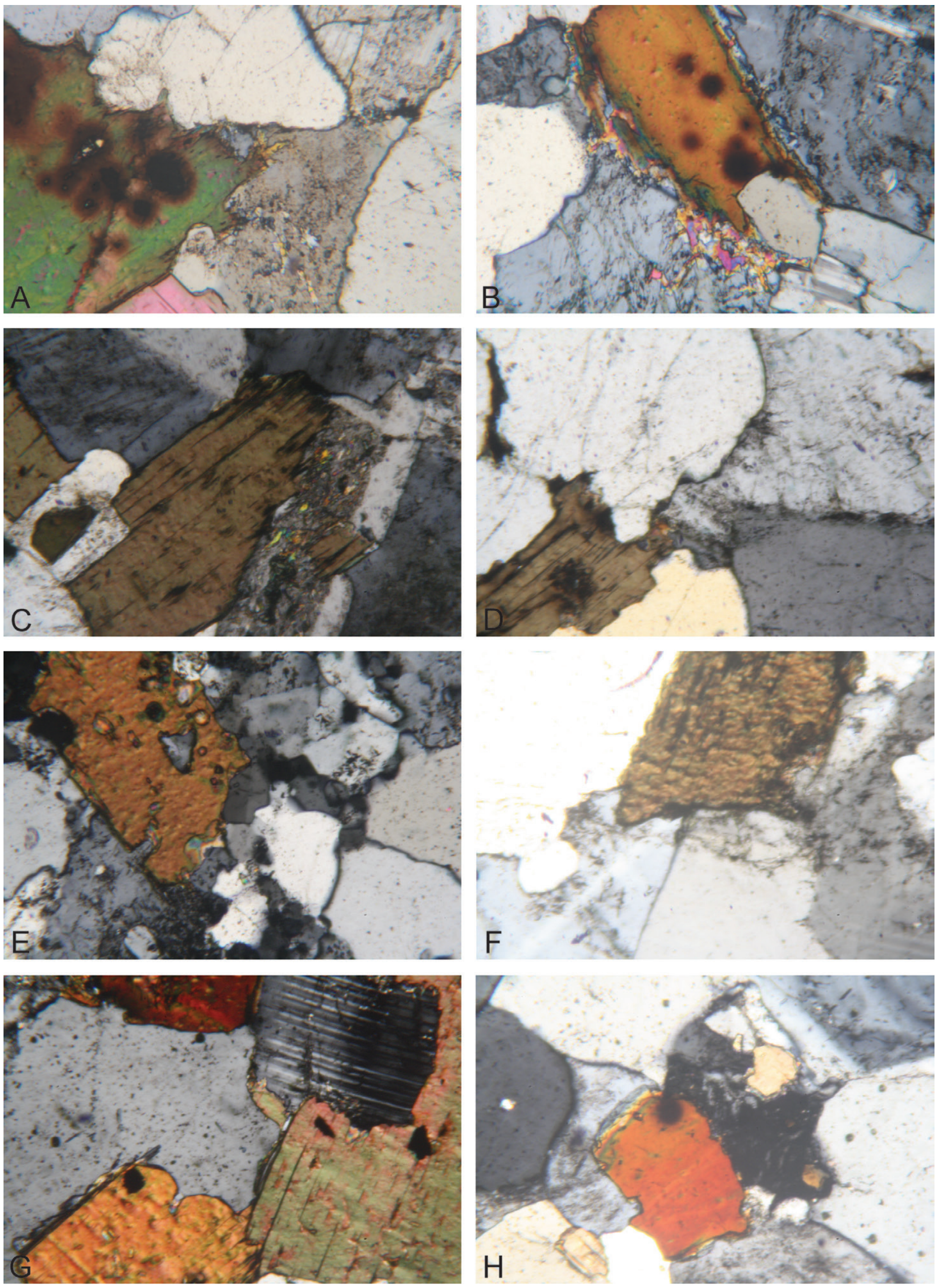

Figure 5. Representative photomicrographs of some of the New England Batholith (eastern Australia) granites investigated for their radiohalos in this study. All photomicrographs are at the same scale (20× or 1 mm = 40μm) and the granite is as viewed under crossed polars. **(A)** Mole Granite, RMG-1: quartz, K-feldspar, plagioclase (with sericite), biotite (with radiohalos) **(B)** Mole Granite, RMG-1: quartz, K-feldspar, plagioclase (with sericite), biotite (with radiohalos) **(C)** Hillgrove Granite (RHG-3): quartz, K-feldspar (with sericite), plagioclase (with sericite), biotite **(D)** Stanthorpe Adamellite (RNEG-18): quartz, K-feldspar, plagioclase, biotite (with radiohalos) **(E)** Uralla Granodiorite (RNEG-3): quartz, K-feldspar, biotite, plagioclase **(F)** Sandy Flat Adamellite (RNEG-5): biotite, K-feldspar, plagioclase **(G)** Mt. Duval Adamellite (RNEG-8): quartz, K-feldspar, plagioclase (with sericite), biotite **(H)** Bungalla Adamellite (RNEG-14): quartz, K-feldspar, plagioclase (with sericite), biotite (with radiohalo).

Table 1. Data table of radiohalos numbers counted in granite samples from various plutons within the New England Batholith, eastern Australia.

Rock Unit	Sample Number	Location		Number of Slides	Numbers of Radiohalos					Number of Radiohalos per Slide	Number of Po Radiohalos per Slide	Ratio ^{210}Po:^{238}U
		Latitude (S)	Longitude (E)		^{210}Po	^{214}Po	^{218}Po	^{238}U	^{232}Th			
Moonbi Adamellite	RNEG-1	30°52’36.4”	151°6’25.4”	50	49	–	2	16	–	1.34	0.98	3.2:1
Uralla Granodiorite	RNEG-3	30°44’49.1”	151”24’43.6”	50	421	–	6	76	–	10.06	8.54	5.6:1
	RNEG-7	30°41’52.1”	151°28’7.4”	50	195	–	–	25	–	4.40	3.90	7.8:1
Bolivia Range Adamellite	RNEG-4	29°19’4.8”	151°55’28.7”	50	235	–	–	59	–	5.88	4.70	4:1
Sandy Flat Adamellite	RNEG-5	29°11’56.8”	152°0’40.6”	50	243	–	–	66	–	6.18	4.86	3.7:1
Bendemeer Adamellite	RNEG-6	30°53’8.4”	151°9’32.4”	50	83	–	–	52	–	2.70	1.66	1.6:1
Mt Duval Adamellite	RNEG-8	30°26’13.6”	151°40’22.9”	50	335	–	–	167	–	10.04	6.70	2:1
Llangothlin Adamellite	RNEG-9	30°7’16.1”	151°41’13.7”	50	35	–	–	19	–	1.08	0.70	1.8:1
Shannonvale Granodiorite	RNEG-10	29°50’37.1”	151°44’19.6”	50	52	–	–	5	–	1.14	1.04	10.4:1
Tent Hill Porphyrite	RNEG-11	29°31’32.3”	151°40’26.5”	50	–	–	–	–	–	–	–	–
Dundee Adamellite	RNEG-12	29°29’22.6”	151°40’57.1”	50	22	–	–	1	–	0.46	0.44	22:1
Kingsgate Granite	RNEG-13	29°26’0.9”	151°52’6.8”	50	113	–	–	26	–	2.78	2.26	4.4:1
Bungulla Adamellite	RNEG-14	29°8’19.3”	151°59’47.0”	50	156	–	–	27	–	3.66	3.12	5.8:1
Undercliffe Falls Granite	RNEG-15	28°38’34.2”	152°10’29.9”	50	3	–	–	–	–	0.06	0.06	–
Stanthorpe Adamellite (Granite)	RNEG-2	28°50’8.9”	151°55’14.4”	48	520	5	15	68	19	13.06	11.25	7.9:1
	RNEG-16	28°49’54.9”	151°50’50.6”	50	135	–	–	44	–	3.58	2.70	3.1:1
	RNEG-17	28°45’1.1”	151°53’49.3”	50	382	–	–	45	–	8.54	7.64	8.5:1
	RNEG-18	28°39’13.5”	151°56’45.2”	50	130	–	–	1	–	2.62	2.60	130:1
	RNEG-19	28°35’24.7”	151°57’13.1”	50	131	–	–	7	–	2.76	2.62	18.7:!
	RNEG-20	28°22’37.8”	151°55’7.9”	50	97	–	–	3	–	2.00	1.94	32.3:1
Hillgrove Granite	RHG-1	30°32’8.5”	151°51’22.2”	50	247	–	–	391	–	12.76	4.94	0.6:1
	RHG-2	30°33’19.0”	151°54’36.9”	50	316	4	–	357	–	13.54	6.40	0.9:1
	RHG-3	30°33’57.4”	151°52’32.2”	50	290	4	–	346	–	12.80	5.88	0.8:1
Mole Granite	RMG-1	29°20’21.8”	151°41’30.1”	50	1542	–	–	624	–	43.32	30.84	2.5:1
	RMG-2	29°19’2.9”	151°41’14.8”	50	1323	–	–	547	–	38.15	26.46	2.4:1
	RMG-3	29°18’0.4”	151°39’1.9”	50	1453	–	–	1053	–	50.22	29.06	1.4:1
	RMG-4	29°18’18.5”	151°42’43.4”	50	156	–	–	3	–	3.18	3.12	52:1

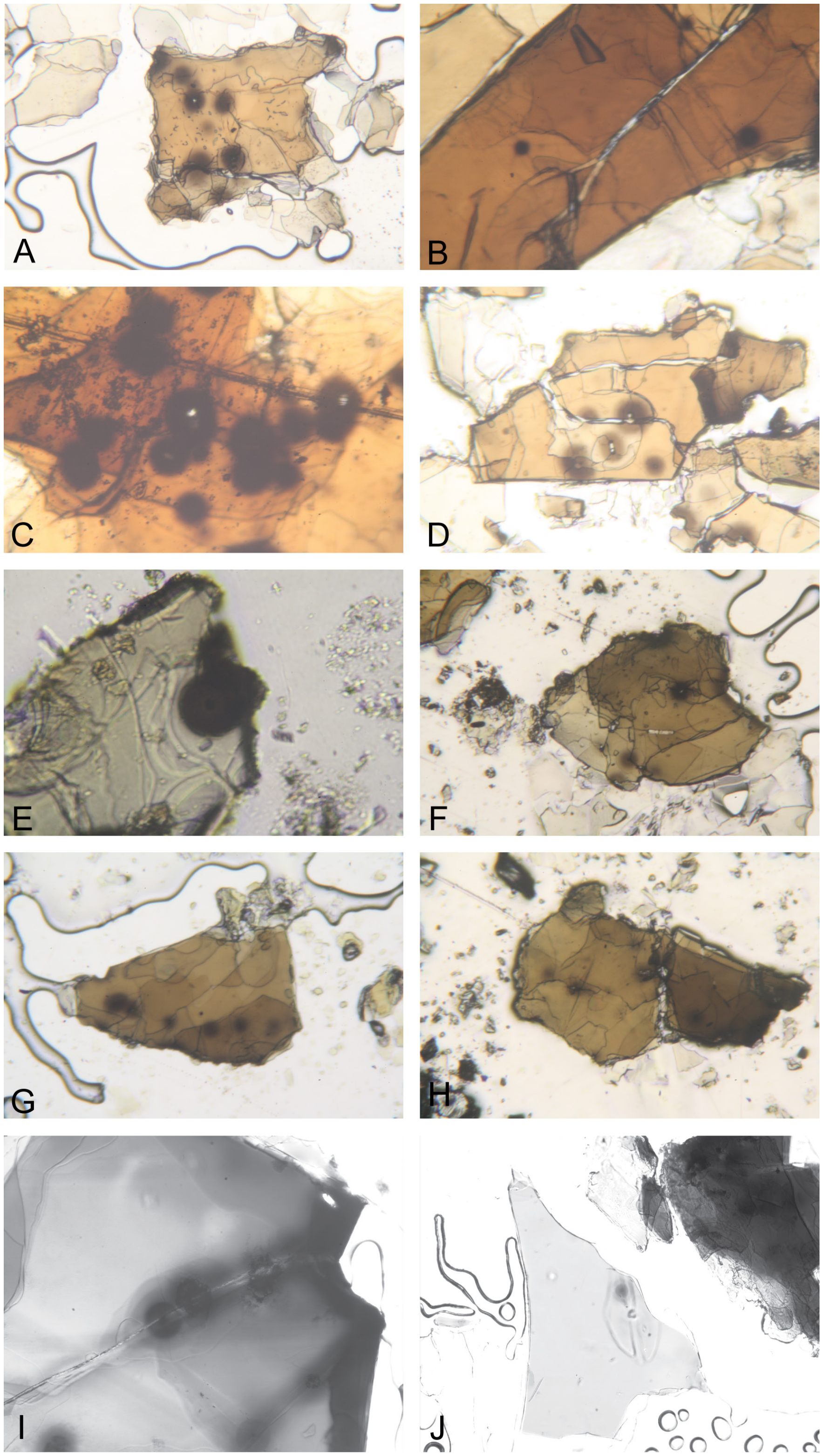

Figure 6. Some representative radiohalos found in biotite flakes separated from some New England Batholith (eastern Australia) granites investigated in this study. Photomicrographs (A), (B), (D), (F)-(H), and (J) are all at the same scale of 40× or 1 mm = 20µm, while photomicrographs (C), (E), and (I) are all at the same scale of 80× or 1 mm = 10µm). All the biotite flakes are as viewed in plane polarized light. **(A)** Mole Granite, RMG-1: overexposed ^{238}U radiohalos **(B)** Mole Granite, RMG-1: a ^{210}Po radiohalo (left) and an overexposed ^{238}U radiohalo (right) **(C)** Mole Granite, RMG-3: overexposed ^{238}U radiohalos (large) and ^{210}Po radiohalos (small) **(D)** Mole Granite, RMG-3: four overexposed ^{238}U radiohalos (large) and three ^{210}Po radiohalos (small), one with an elongated former fluid bubble as its radiocenter **(E)** Hillgrove Granite, RHG-2: an overexposed ^{238}U radiohalo **(F)** Stanthorpe Adamellite, RNEG-17: four overexposed ^{210}Po radiohalos **(G)** Stanthorpe Adamellite, RNEG-17: five overexposed ^{210}Po radiohalos **(H)** Stanthorpe Adamellite, RNEG-17: two overexposed ^{210}Po radiohalos **(I)** Stanthorpe Adamellite, RNEG-2: ^{218}Po radiohalos along two cracks **(J)** Stanthorpe Adamellite, RNEG-2: a ^{214}Po radiohalo.

high total Po radiohalos numbers in the Hillgrove Granite are similar to those in a few samples from four other granite plutons which are not known to host economic hydrothermal vein deposits (427 in the Uralla Granodiorite, 335 in the Mt. Duval Adamellite, 243 in the Sandy Flat Adamellite, and 235 in the Bolivia Range Adamellite), although three of those four plutons contained only low ^{238}U radiohalos numbers (59-76), and the other pluton a moderate number (167). In contrast, two of the five samples of the Stanthorpe Granite which probably hosts hydrothermal ore veins contained high total Po radiohalos numbers (382 and 540). Yet those samples have low ^{238}U radiohalos numbers (45 and 68 respectively).

On the other hand, the samples of the Mole Granite that were obtained from close to known hydrothermal ore veins contained extremely high total numbers of Po radiohalos (1323-1542), in stark contrast (almost 10:1) to the low total number of Po radiohalos (156) in the fourth sample distant from known hydrothermal ore veins. Note that the same three samples close to known hydrothermal ore veins also contained extremely high numbers of ^{238}U radiohalos (547-1058).

DISCUSSION

Snelling and Armitage (2003) and Snelling (2005) proposed the hydrothermal fluid model for Po radiohalo formation. Snelling (2005) also predicted that, as a consequence of this model, in geologic contexts where there have been greater volumes and flows of hydrothermal fluids, there should also be greater numbers of Po radiohalos produced. Snelling (2008b, c, d, 2014) and Snelling and Gates (2009) demonstrated that this consequence of the model was clearly evident in a variety of geologic contexts, thus confirming the model. Snelling (2005) also predicted that because the hydrothermal fluids released by crystallizing and cooling granite plutons had carried metals in solution that were transported and precipitated in fractures as metallic ore veins to produce economic orebodies, then there should be greater numbers of Po radiohalos in those granites where these ore-forming hydrothermal fluids have flowed. He thus suggested that Po radiohalos numbers in granites might be a useful pathfinder exploration tool for the discovery of otherwise hidden hydrothermal metallic ore-vein deposits.

The results of this study very clearly support this proposition made by Snelling (2005) that high Po radiohalo numbers should be found in granites associated with hydrothermal ore veins. The almost 10:1 ratio of Po radiohalos numbers in the three samples of the Mole Granite near known commercially-exploited ore veins (RMG-1, 2, 3) compared with the one sample distant to them (RMG-4) is consistent with this. Table 1 lists those three samples with total Po radiohalos numbers of 1323-1542, compared to the distant sample with only 156. Note that the ratio of ^{210}Po to ^{238}U radiohalo numbers (Table 1, last column) is not as indicative of proximity to ore veins as is the total number of Po radiohalos. This is because the higher numbers of Po radiohalos result from a higher volume of flow of hydrothermal fluids, which also transported and deposited metals in the adjacent ore veins.

Additionally, there is not only this correlation of the extremely high total Po radiohalos numbers in the Mole Granite with the proximity to the ore veins, but also a similar correlation with the extremely high numbers of ^{238}U radiohalos in the same three samples (547-1058) compared to the distant sample (3). The ^{210}Po:^{238}U radiohalos ratios of the three samples proximal to the ore veins are 1.4:1 – 2.5:1, while that of the distal sample is 52:1. No other granite plutons sampled in this study have such high numbers of ^{238}U radiohalos, but it makes sense that if a granite has large numbers of U-bearing zircons capable of producing so many ^{238}U radiohalos, then as the U in the zircons decays it provides a large source of Po to the hydrothermal fluids to produce the large numbers of adjacent Po radiohalos.

The Mole Granite is a leucoadamellite or leucocratic granite whose high SiO_2 (76.68%) and Al_2O_3 (12.19%) contents (Shaw and Flood 1981) makes it corundum normative and thus of I-type (igneous protolith) affinity. And as is typical of Sn-W hydrothermal ore-generating granites, it contains topaz [$Al_2SiO_4(F,OH)_2$], which is indicative of the high level of volatiles such as F that were in the hydrothermal fluids expelled as the granite cooled. Hong et al. (2017) found that the Tasmanian granites associated with very large hydrothermal Sn-W ore deposits are also typically I-type leucocratic granites (73-76% SiO_2), are commonly porphyritic with K-feldspar megacrysts, and contain biotite, topaz and/or fluorite, and trace to accessory zircon.

However, Hong et al. (2017) also reported that the trace to accessory amounts of zircon was not a diagnostic feature of the Tasmanian granites associated with the very large hydrothermal Sn-W ore deposits. Even barren I-type Tasmanian granites were leucocratic with trace amounts of zircon. As predicted by Snelling (2005) and verified by Snelling (2008b, c, d, 2014) and Snelling and Gates (2009), what is critical for production of Po radiohalos is not necessarily the quantities of zircons in granites, but zircons with a moderate to high U content in granites where there are also large flows of hydrothermal fluids containing magmatic volatiles capable of transporting the Po generated by U decay in the zircons.

The water content of granite magmas varies according to their composition which reflects their sources (Holtz et al. 1995; Huang and Wyllie 1975). Water solubility in granitic melts increases with pressure. Whereas at 1 kbar (generally equivalent to 3–4 km depth) the water solubility is 3.7 wt % (Holtz et al. 1995), at 30 kbar (up to 100 km depth, though very much less in tectonic zones) it is approximately 24 wt % (Huang and Wyllie 1975). Following the emplacement of a granitic magma, as crystallization proceeds the concentration of water still dissolved in the residual melt dramatically increases by several orders of magnitude (Snelling 2008a). The vapor pressure increases until the aqueous fluid is forced to flow through a three-dimensional fracture network it produces in the granite out into the surrounding host strata. Meteoric water in the host strata penetrates the fractured pluton, establishing a convective hydrothermal circulation in both the pluton and the host strata, the total amount of water involved being at least equivalent to the pluton's mass. Huge amounts of hydrothermal fluids are thus available to transport Po within granites, and dissolved metals out of granites into fractures to produce ore veins (Cathles 1991).

Most granites contain trace amounts of zircon and high levels of U compared with most other rocks. All zircons contain some U, so will produce Po from the U decay. But only zircons with high U

contents produce ^{238}U radiohalos. In many of these granites most ^{238}U radiohalos are overexposed, implying each zircon radiocenter contained high U, thus producing a lot of Po and potentially many Po radiohalos.

The Mole Granite has a high level of U of up to 27 ppm (Audétat et al. 2000b), and its high topaz content with the associated metallic ore veins indicates high flows of volatile-rich hydrothermal fluids occurred. This explains the extremely high numbers of both Po and ^{238}U radiohalos in the samples of the Mole Granite proximal to the hydrothermal ore veins.

But what of the Hillgrove Granite which likewise has associated hydrothermal ore veins, yet lower numbers of both Po and ^{238}U radiohalos compared to the Mole Granite (Table 1)? As already noted, the Po and ^{238}U radiohalos numbers in the Hillgrove Granite are still high compared to the lower numbers in many of the granite plutons barren of any known hydrothermal ore veins, though they are comparable to several other barren granite plutons (the Uralla Granodiorite, Bolivia Range Adamellite, Sandy Flat Adamellite, and Mt. Duvall Adamellite). Yet apart from the Mt. Duval Adamellite, all the sampled barren granite plutons have low ^{238}U radiohalo numbers.

What makes the Hillgrove Granite different from all the other sampled granites though is that the numbers of both Po and ^{238}U radiohalos are high and approximately equal. And this is the case even for the sample (RHG-1) distal to the Au-Sb-W ore veins. The ^{210}Po:^{238}U radiohalos ratios of all three samples are in the tight range of 0.6:1 – 0.9:1 because ^{238}U radiohalos slightly outnumber ^{210}Po radiohalos. Thus, could it be that the high numbers of both Po and ^{238}U radiohalos may not necessarily be related to the associated Au-Sb-W ore veins? Two observations are relevant.

First, the Hillgrove Granite is an S-type granite, in contrast to all the other sampled granite plutons, apart from the Bendemeer Adamellite of the Bundarra Plutonic Suite. S-type granites are generated from sedimentary protoliths which as such have different compositions, trace element levels, and often lower water contents that are incorporated into the resultant granitic magmas, compared to those of I-type, igneous-protolith-generated granitic magmas. Yet even though the S-type Bendemeer Adamellite contains similar moderate numbers of Po and ^{238}U radiohalos, they are much lower numbers than those found in all three Hillgrove Granite samples, both distal and proximal to the ore veins (Table 1). These considerations therefore suggest that the higher and similar numbers of Po and ^{238}U radiohalos in the Hillgrove Granite are related to the composition of the sedimentary protolith from which it was generated. The Hillgrove Granite obviously has more zircons with reasonable U contents in it than in the Bendemeer Adamellite to have generated both the many ^{238}U radiohalos and many Po atoms from U decay, plus a reasonable localized flow of hydrothermal fluids within the cooling pluton to have then transported the many Po atoms to generate the similar number of Po radiohalos.

Second, while the Hillgrove Granite has the Au-Sb-W ore veins associated with it, the structural relationships in the Hillgrove area as already described indicate that hydrothermal fluids from the Hillgrove Granite did not form the ore veins. After intrusion of the Hillgrove Granite both the granite and the host metasediments were deformed, resulting in variably developed foliation and the formation of steeply-dipping mylonite zones, including major faults. The Bakers Creek Diorite Complex (Fig. 2) was then intruded before the whole area suffered further deformation and regional greenschist facies metamorphism. It was subsequent to this that a further magmatic episode generated the hydrothermal ore veins which transect the Hillgrove Adamellite, the host metasediments, and Bakers Creek Diorite Complex, and which developed coevally with the emplacement of shoshonitic lamprophyre dikes that commonly occupy the same fractures and structures (Ashley et al. 1994) (Fig.2).

Thus, the Au-Sb-W ore veins were not produced by expulsion of hydrothermal fluids from the Hillgrove Granite. The lamprophyres have geochemical and temporal affinities with the mafic granitoid (monzonite) members of the high-K, I-type Moonbi Plutonic Suite, the nearest intrusions of which crop out about 15 km from Hillgrove.

Such a distal source of the hydrothermal fluids is consistent with the fluid inclusion filling temperatures of 100-250°C in quartz from the Hillgrove ore veins (Comsti and Taylor 1984), compared with the homogenization temperatures of 220-580°C for fluid inclusions in quartz from the ore veins within the Mole Granite (Audétat et al. 2000a; Plimer et al. 1995). Furthermore, the hydrothermal fluids have different salinities, 1.8 to 4.8 wt.% NaCl equivalent for the Hillgrove ore veins compared to 20 to 60 wt.% salts for the Mole Granite ore veins. Clearly, the hydrothermal fluids expelled from the cooling distal Moonbi Suite granitoids with the lamprophyre dikes lost temperature and salinity by reaction with the host rocks they passed through, and by mixing with the groundwaters adjacent to the fractures they traversed on their way to eventually depositing the Au-Sb-W ore veins 15 km distant. Ore veins are known to form even up to 20 km distant from the granite pluton sources of the metal-transporting hydrothermal fluids, for example, around the Cornubian Batholith of Cornwall, England (Černý et al. 2005). In any case, the hydrothermal fluids expelled from the Moonbi Suite granitoids were transported with the lamprophyre dikes as a continuing heat source along faults and major fractures (Ashley et al. 1994). Then it was likely that the lower temperatures and salinities at that distance from the granitoids resulted in those metals precipitating from solution in the hydrothermal fluids. By contrast, the ore veins produced from the hydrothermal fluids expelled by the Mole Granite were precipitated in the margins of that granite, and in the immediately adjacent host rocks forming the roof to the cooling pluton.

Several I-type Moonbi Suite granite plutons were sampled in this study – the Moonbi Adamellite, Sandy Flat Adamellite, Kingsgate Granite, Bungulla Adamellite, and Undercliffe Falls Granite (Table 1 and Fig. 1). Of these only the Sandy Flat Adamellite had a similar number of Po radiohalos (243) to the Po radiohalo numbers in the Hillgrove Granite (247-320). However, unlike the S-type Hillgrove Granite, all these sampled granite plutons of the I-type Moonbi Suite had much lower numbers of ^{238}U radiohalos compared to their Po radiohalos numbers (Table 1). Thus, the hydrothermal fluids responsible for the Hillgrove ore veins likely did not have a Moonbi Suite granitoid source containing lots of U-bearing zircons,

and therefore did not transport much Po. Besides, because of the very short half-lives of the Po isotopes in the U-decay chain any Po dissolved in those hydrothermal fluids would have decayed during transport through the fractures over such long distances (at least 15 km) before reaching the Hillgrove Granite. And any Po transported by those hydrothermal fluids may not have had any impact on the Po radiohalo numbers in the already cooled Hillgrove Granite.

Thus, the Po radiohalos within the Hillgrove Granite must have formed only from the hydrothermal fluids expelled locally within that cooling pluton (within its biotite grains), which is consistent with the similar high numbers of Po radiohalos in both the two samples (RHG-2, 3) near the ore veins and the sample (RHG-1) distal to them (Table 1). On the other hand, the two samples near the ore veins do contain slightly higher ^{210}Po radiohalo numbers (290 and 316) plus four (4) ^{214}Po radiohalos each, compared with the 247 ^{210}Po radiohalos in the sample distal to the ore veins. However, with such a small number of samples it is perhaps premature to attribute this difference in Po radiohalo numbers to any influence of the later hydrothermal fluids responsible for the ore veins on those portions of the Hillgrove Granite proximal to the ore veins.

Nevertheless, those later hydrothermal fluids did penetrate and hydrothermally alter the wall-rocks to the ore veins they formed (Ashley et al. 1994), including the Hillgrove Granite. Therefore, those hydrothermal fluids may have potentially transported some Po from the U decaying in the zircon centers to ^{238}U radiohalos within biotite grains in the Hillgrove Granite proximal to the ore veins to generate a few more Po radiohalos to those already in the Hillgrove Granite from its own hydrothermal fluids expelled when it cooled. Indeed, with an annealing temperature of only 150°C (Laney and Laughlin 1981) all the radiohalos had to form below that temperature (Snelling and Armitage 2003; Snelling 2005). So, given hydrothermal fluid temperatures of 100-250°C for the formation of the Hillgrove Au-Sb-W ore veins, further Po radiohalo formation in the granite wall-rock is feasible.

Finally, there are the six samples from the Stanthorpe Adamellite with very different radiohalo numbers in them, ranging from sample RNEG-2 with 540 Po radiohalos to RNEG-20 with only 97 (Table 1). Indeed, two of the Stanthorpe Adamellite samples have Po radiohalos numbers higher than the Po radiohalos numbers in the Hillgrove Granite samples, though not nearly as high as the Po radiohalos numbers in the Mole Granite. Yet like the Mole Granite, the ^{238}U radiohalos numbers in all the Stanthorpe Adamellite samples are comparatively lower than the Po radiohalos numbers in each sample, with ^{210}Po:^{238}U radiohalos ratios of 3.1:1 to 130:1.

The name of the town of Stanthorpe, that gives its name to this granite on which it sits and which surrounds it, literally means “tin town”, as *stannum* is Latin for “tin” and *thorpe* is Middle English for “village”. Historically, the town sprang up around alluvial tin mining in that location from 1872 onwards. That alluvial cassiterite is assumed to have been released from the Stanthorpe Granite as it weathered. Indeed, Shaw and Flood (1981) refer to the Stanthorpe Granite as a Sn-bearing muscovite leucoadamellite. However, it is not clear whether there were hydrothermal Sn ore veins in the Stanthorpe Granite or whether the cassiterite was simply dispersed throughout the granite as an accessory mineral. Nevertheless, the former Sundown Sn and Cu mine obviously exploited a Sn-Cu hydrothermal orebody within the Stanthorpe Adamellite. But that mine is downstream from where the alluvial Sn was recovered, so that orebody could not have been the source of the alluvial Sn. And given the local history, it is likely that the Stanthorpe Adamellite and its surrounding area have over the years been well prospected for easily detected, nearly surface Sn ore veins.

However, based on the results of this study it might be possible to predict that some as-yet-undiscovered hydrothermal Sn ore veins may exist in and near the Stanthorpe Adamellite. The presence of high Po radiohalos numbers in samples of the Mole Granite proximal to known hydrothermal Sn-W ore veins in contrast to a granite sample from a barren area clearly indicates the potential for Po radiohalos as a pathfinder in exploration for the discovery of new ore veins in that and other granites. Thus, in the Stanthorpe Adamellite the Po radiohalos numbers in samples RNEG-2 and RNEG-17 (540 and 382 respectively, Table 1and Fig. 1) could be interpreted as significantly above the background Po radiohalos numbers to warrant further investigative sampling in those proximities, although sample RNEG-2 is from within a national park.

Three final relevant observations should also be noted. In Fig. 6(d) can be seen a ^{210}Po radiohalo surrounding a radiocenter which consists of an elongated fluid “bubble”. Additionally, in Fig. 6(i) the ^{218}Po radiohalos occur along cracks in the biotite flake. Both these observations confirm the role of hydrothermal fluids in transporting the Po isotopes and their ^{226}Ra and ^{222}Rn precursors, as per the hydrothermal fluid transport model of Snelling and Armitage (2003) and Snelling (2005). According to that model the hydrothermal fluids released as the granite crystallizes and cools transport those isotopes from the decaying ^{238}U in nearby zircon crystals along the cleavage planes between the sheets in the biotite structure and along cracks, to sites where the Po isotopes are precipitated into radiocenters which produce the ^{218}Po, ^{214}Po and ^{210}Po radiohalos. Which of these Po radiohalos are produced depends on the timeframe for the transport of the ^{226}Ra and ^{222}Rn and of the precipitation of the Po isotopes.

In the case of the ^{210}Po radiohalo in Fig. 6(d), the transport in the fluid and nucleation of the bubble was so slow over many days that the decay chain had resulted in only ^{210}Po being left to form a radiohalo. On the other hand, in Fig. 6(i) there must have been a chemical environment along the crack which resulted in the ^{218}Po being precipitated from the fluids transporting ^{222}Rn along the crack immediately the ^{222}Rn decayed into ^{218}Po. Otherwise, if the ^{218}Po wasn’t precipitated immediately within a short timeframe due to the ^{218}Po half-life of 3.1 minutes, then the ^{218}Po radiohalo ring would not have been produced. Thus, these observations confirm the hydrothermal fluid model for the formation of the Po radiohalos, and the rapid timescale for their formation. This is also testimony to the hydrothermal fluids being present in the granite as it cooled that could transport other metals to also produce hydrothermal ore veins rapidly.

Finally, if the Po were dissolved, transported and precipitated by the hydrothermal fluids as ^{210}Po it might be argued that with a half-life of 138 days the resultant ^{210}Po radiohalos might take years to form.

And would it be possible to have rapid transport of small amounts of fluids to produce the ^{210}Po radiohalos and deposit the ore veins over long periods (or intermittent periods) of time? In response there are several key factors to remember. First, it is only due to the accelerated U decay that a large "pulse" of Po isotopes was generated, and that was primarily only during the year of the Flood. Second, the heat sources to drive the large flows of hydrothermal fluids were the crystallizing granite plutons. Since they cooled rapidly (Snelling 2008a), then these heat sources and the large flows of hydrothermal fluids were also only short-lived within the Flood year, especially as the fossiliferous sediment layers the granite plutons intrude had to be first deposited during the Flood year. So all these factors combine to constrain the timescale for the formation of both Po radiohalos and ore veins.

In conclusion, it is evident from this study that Po radiohalos could be used successfully as a pathfinder tool in the exploration for hydrothermal ore veins related to granites, in new areas within districts with known granite-related hydrothermal ore veins, and even in new districts with prospective granites. However, further work to develop this tool is encouraged, including more extensive collections of samples, perhaps even on a grid over a prospective granite, as it would bring the significance of Po radiohalos to the attention of the conventional geological community.

Furthermore, the large numbers of Po radiohalos in the Mole Granite associated with the hydrothermal ore veins within and in close proximity to that granite are also a confirmation of the hydrothermal fluid transport model for the formation of Po radiohalos. And by implication this constrains the timeframe for deposition of the ore veins themselves. Since the same hydrothermal fluid flows responsible for the Po radiohalos within that granite were responsible for forming the ore veins associated with it, then the ore veins must have formed in the same very rapid timescale as that for the formation of the Po radiohalos, that is, within weeks, a timescale fully compatible with the biblical chronology of earth history.

CONCLUSIONS

Both the Hillgrove and Mole Granites of the New England Batholith of eastern Australia have economically-exploited hydrothermal ore veins associated with them. However, only the Mole Granite was found to contain extremely high numbers of Po radiohalos (1323-1542) in the three samples of it in close proximity to known ore veins. In stark contrast, the one Mole Granite sample distant from known ore veins contained only low-moderate numbers of Po radiohalos (156, or almost 90% fewer). On the other hand, two samples of the Hillgrove Granite proximal to its associated ore veins and one sample distal to them all contained moderate-high numbers of Po radiohalos (247-320), numbers similar to those in barren granite plutons elsewhere in the batholith. But unlike the Mole Granite samples associated with ore veins which had ^{210}Po:^{238}U radiohalos ratios of 1.4:1 to 2.5:1, all the Hillgrove Granite samples had ^{210}Po:^{238}U radiohalos ratios of 0.6:1 to 0.9:1, that is, more ^{238}U radiohalos than ^{210}Po radiohalos. This was not only attributable to the protolith of the S-type Hillgrove Granite potentially having fewer zircons with less U, but because the ore veins were not produced from the hydrothermal fluids expelled from that cooling pluton. Rather, the Hillgrove ore veins were precipitated from hydrothermal fluids as distant granitoid plutons cooled in a later magmatic event.

Thus, the extremely high numbers of Po radiohalos in those Mole Granite samples proximal to known ore veins successfully indicated their proximity to those ore veins. It logically follows, therefore, that the Po radiohalos proved to be a reliable pathfinder for the hydrothermal ore veins associated with the sampled granite which produced and hosted those ore veins. This strategy was then applied to the Stanthorpe Granite, which historically has one exploited hydrothermal Sn-Cu vein deposit and yielded alluvial Sn. Two samples with high to very high numbers of Po radiohalos (382-540) in contrast to low numbers of ^{238}U radiohalos potentially pinpoint areas within that granite that could be subjected to follow-up exploration for possible hydrothermal Sn ore veins, nearby and/or at depth. It is recommended that further work to develop this tool is encouraged, including more extensive collections of samples, perhaps even on a grid over a prospective granite. Nevertheless, since the same hydrothermal fluid flows responsible for the Po radiohalos within the Mole Granite were responsible for forming the ore veins associated with it, then the ore veins must have formed in the same very rapid timescale as that for the formation of the Po radiohalos, that is, within weeks, a timescale fully compatible with the biblical chronology of earth history.

ACKNOWLEDGMENTS

The assistance of Mark Armitage in processing the samples and scanning them for radiohalos was appreciated.

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