Post-intrusion heating associated with high-heat-producing Proterozoic granites — implications for mineralisation?

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Mineral deposits in Australian Proterozoic terrains are commonly associated spatially and temporally with granitic intrusives. Accordingly, the granites are perceived as the sources of advective heat and metal-bearing fluids in the mineralisation process. In places, however, mineral deposits are as much as 40 m.y. younger than a spatially associated intrusive, and the origin of their mobilising and transporting fluid(s) remains enigmatic. We propose a model in which radiogenic decay may initiate a second stage of hydrothermal circulation, and thus create an alternative mechanism for mineralisation that is spatially associated with Proterozoic granites. This model also contributes to the debate about why certain fluids spatially associated with granite intrusives have a mainly 'magmatic' character, while others in the same area have properties that are better classified as 'meteoric', 'metamorphic', or 'basinal'.

Fundamentals of a prolonged-heating model

Australian Proterozoic granites are characterised by elevated to extreme enrichments of the heat-producing elements — U, Th, and K. Although this phenomenon is not confined to Australian examples, the level of enrichment in terrains such as the Mount Isa, Pine Creek, and Mount Painter Inliers is anomalous on a global scale (Table 2). As granites within these terrains retain a primary igneous Th:U ratio of ~3.5–4.5 (Durrance 1986: 'Radioactivity in geology: principles and applications', Halstead Press, New York), their high heat production is not simply a result of post-crystallisation alteration. Accordingly, we suggest that the intrusion of such enriched granites results in two hydrothermal circulation mechanisms due to:

- advective heat during intrusion; and
- prolonged radiogenic decay of heat-producing elements in the granite.

Regardless of the source area, the intrusion of an anomalously radiogenic granitic magma results in fundamental changes to the crustal thermal structure, both above and below the intrusive level. The specific thermal effects will depend primarily on the total radiogenic heat production of the granite, but also on the depths of the magma source and intrusion and their relative length scale (i.e., the ratio of the width of the intrusion to the width of the source). The additional heat flowing from the mantle will also contribute to the thermal effects. Our qualitative modelling relates to the instantaneous emplacement of a magma (a reasonable approximation, as magmas must ascend fast enough to prevent conductive heat loss) in the upper crust at a depth of ~12 km (Fig. 23).

As a consequence of an intruding magma, advection causes a local transient thermal perturbation immediately around it. This is the mechanism by which classic metamorphic aureoles are formed, and may also give rise to what are loosely termed 'thermal-aureole Au deposits' (Wall & Taylor 1990: Geological Society of Australia, Abstracts, 25, 264–265). The intrusion of a granite of 'Williams Batholith-like' characteristics from a lower-crustal source causes an advective thermal anomaly (T_a, Fig. 24A) that extends only ~5 km from the granite margin and lasts for only ~2–4 m.y. After this time, in the absence of other heat sources, the system will rapidly return to steady-state background temperatures.

However, for granites with high concentrations of U, Th, and K, the decay of these radiogenic elements causes a second stage of heating (T_R, Fig. 24B; Fig. 25). This produces a prolonged broad thermal perturbation which is recorded up to 10 km from the granite margin. This heating has a low intensity (an additional ~40°C above background immediately surrounding the granite, and up to an extra 15°C ~10 km from the margin), but may be sustained for up to 300 m.y.

Hydrothermal fluids may circulate in response to thermal gradients within porous media. The long-term upper-crustal heating induced by radiogenic decay sustains locally elevated geothermal gradients, promoting circulation of hydrothermal fluids long after the intrusion of the magma. The potential to establish such enduring and extensive fluid-circulation systems at elevated temperatures has important implications for the leaching and deposition of metals.

Application of the prolonged-heating model to thermal-aureole gold deposits

In the eastern Mount Isa Inlier, the Ernest Henry, Starra, and Mount Elliott Cu–Au deposits are adjacent to the high-heat-producing Williams and Naraku Batholiths (Table 2). Within analytical error, the mineralisation at both Mount Elliott and Starra was essentially coeval with batholith emplacement (ca 1510–1485 Ma; Perkins & Wyborn 1998: Australian Journal of Earth Sciences, 45, 233–246). However, mineralisation at Ernest Henry, and some of the regional alteration within the Williams and Naraku Batholiths, followed granite intrusion by as much as 20 m.y. (Perkins & Wyborn 1998: op. cit.).

Similarly in the Pine Creek Inlier, the emplacement of the Cullen Batholith ($H = 5.8\ \mu W\ m^{-3}$) preceded spatially related tin deposition by ~20 m.y., and gold mineralisation by ~40 m.y. (Klominsky et al. 1994: 'Radiothermal granites of the Cullen Batholith and associated mineralization', Czech Geological Survey, Special Papers, 5). According to Klominsky et al. (1994: op. cit.) and Partington & McNaughton (1997: Chronique de la Recherche Miniere, 529, 25–44), mineralisation in this terrain was a multistage process, principally involving hydrothermal mobilisation related to the internal heat of the batholith, rather than its advective heat.

In addition to accounting for the time delay between intrusion and mineralisation in these examples, the results of 2D finite-element modelling presented here also explain the close spatial relationship between mineral deposits and these high-heat-producing granites. For example, in the Pine Creek Inlier, gold has been deposited as a halo about 5 km from the margin of the Burnside Granite (Stuart-Smith et al. 1993: 'Geology and mineral deposits of the Cullen Mineral Field, Northern Territory', AGSO Bulletin 229). Thermal effects due to magmatic heating are minimal at these distances (Fig. 24A), but prolonged heating due to radiogenic decay may be significant.

Application of the prolonged-heating model to other deposit styles

High-heat-producing granites may also contribute to the formation of other styles of mineral deposit that are commonly related to basinal or low-temperature metamorphic processes. The Mount Isa Cu deposit, for example, occupying a greenschist-facies terrane, and the high-heat-producing Sybella Batholith, in an amphibolite-facies terrane, are juxtaposed either side of the Mount Isa Fault. This Cu deposit formed at ~1523 Ma, which is essentially coeval with the Isan Orogeny (Perkins et al. in press: Economic Geology) but much younger than the emplacement of the Sybella Batholith (~1670 Ma; Page & Bell 1986: Journal of Geology, 94, 365–379). Hydrothermal fluids deposited the Mount Isa copper at ~300°C (Heinrich et al. 1995: Economic Geology, 90, 705–730), but their circulation must have been activated by a mechanism other than the high-grade metamorphism in the adjacent terrain, which was uplifted to its present position no earlier than 1460 Ma (Perkins et al. in press: Economic Geology). Instead, regional-scale convection cells due to low-amplitude radiogenic heating in the Sybella Batholith may have provided the driving force for the mineralisation. McLaren et al. 1998 (Geological Society of Australia, Abstracts, 49, 305) assert that the high geothermal gradients associated with the Isan Orogeny in the area adjacent to the Mount Isa Cu deposit were simply due to the known radiogenic-heat capacity buried in the crust without any additional advective component.

Solomon & Heinrich (1992: Exploration Mining Geology, 1, 85–91) have also suggested that radiogenic heat played a role in the generation of the associated Mount Isa Pb–Zn deposits.

Table 2. Geochemistry and present-day heat production

Granite unit	*U (ppm)*	*Th (ppm)*	*K_2O (wt%)*	*Th:U*	*Q ($\mu W m^{-3}$)**
Average granite	4	15	3.5	3.8	2.5
MII — Williams Batholith	13	55	3.9	4.3	7.8
MII — Naraku Batholith	10	57	3.5	5.7	7.1
MII — Sybella Batholith	8	35	5.1	4.3	5.1
PCI — Cullen Batholith	9	39	5.0	4.1	5.8
PCI — Burnside Granite	17	48	5.5	2.8	8.4
MPI — Terrapinna Granite	9	55	5.6	5.9	7.0
MPI — Mount Neill Granite	19	67	3.5	3.5	10.2

Q = present heat production, calculated from present concentrations of U, Th, and K.
MII = Mount Isa Inlier, PCI = Pine Creek Inlier, MPI = Mount Painter Inlier. Average granite values are from Fowler 1990 ('The solid Earth', Cambridge University Press, New York). MII data from Wyborn et al. 1988 (Precambrian Research, 40/41, 509–541). PCI data from AGSO's ROCKCHEM database.
* As radioactive decay causes a reduction in the concentration of heat-producing elements through time, the value of the calculated heat production at the time of intrusion of each batholith would have been on average ~25–30% higher than the present day value quoted above; thus, when it intruded at 1670 Ma, the Sybella Batholith's heat production would have been 6.8 (compared with its current 5.1) $\mu W m^{-3}$.

Discussion

These examples provide an insight that may help to explain both the close spatial and temporal relationships between Proterozoic mineralisation and radiogenic granitic intrusion. Importantly, this need not necessarily be a strictly temporal association. Secondary or later hydrothermal circulation cells developed above and adjacent to granite are simply responding to long-term crustal heating due to radiogenic decay within the granite. Fluids associated with these later hydrothermal circulation cells will have an increasingly meteoric or metamorphic character and may overprint earlier fluid events that are more magmatic in character. This explanation contributes to the current debate as to whether fluids associated with mineral districts that spatially are related to granites will exhibit a magmatic or meteoric/basinal/metamorphic signature (e.g., Tennant Creek, Telfer, Tanami).

Hence, as a result of a single intrusive event there are two possible mechanisms for generating fluid circulation and thus facilitating ore precipitation. The first occurs almost instantaneously after intrusion, and is driven by advective heat. The second is driven by subsequent radiogenic decay in the granite, and has the potential to be maintained for up to 300 m.y. Once radiogenic hydrothermal activity has been initiated, the potential for mineralisation then depends on other factors — including the presence of a source of metals, and specific fluid pathways and depositional conditions.

The modelling presented above demonstrates that a radiogenic heat source in the local environment cannot be underestimated.

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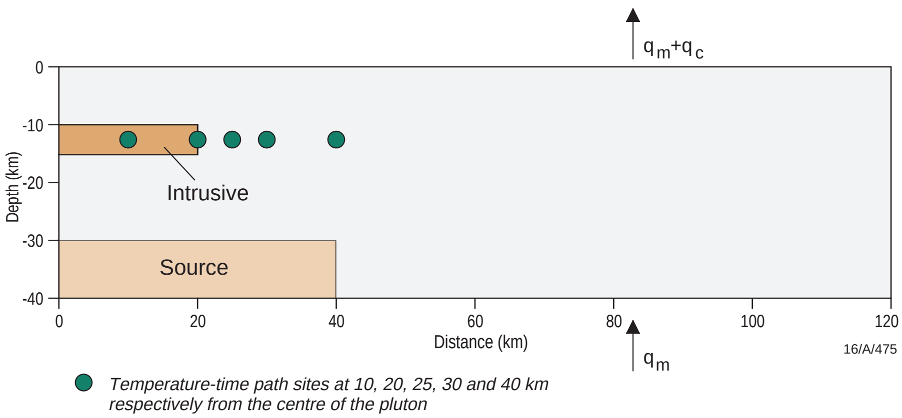

Fig. 23 ***(top left).*** **Schematic-model x–y section showing the parameters and geometry used for the finite-element model discussed in the text. The crustal section, in the semi-infinite half-space as shown, is 40 km thick and 120 km wide. After the melting of a lower crustal source, a magma 4 km thick and 20 km wide intrudes the upper crust at a depth of 12 km. We then follow the thermal evolution of this magma during and after crystallisation for a period of 300 m.y. Owing to its greater volume (40 × 10 km), the source is characterised by a lower volumetric heat production than the product melt. The background, on which the source and intrusion are superposed, is characterised by an exponentially decaying (Lachenbruch-like) heat-production distribution with a characteristic length scale of decay of 22.5 km and an integrated contribution to the surface heat flow (q_c) of 45 mW m^{-2}. The mantle contribution to surface heat flow (q_m) is constant at 20 mW m^{-2}, and the thermal conductivity, considered to be depth-independent, is taken to be 2.5 W m^{-1} K^{-1}. All temperature–time-path sites are at a depth of 12 km (corresponding to the depth centre of the pluton) and at varying distances from the pluton centre (10, 20, 25, 30, and 40 km); the individual temperature–time paths for these points are shown in Figure 24.**

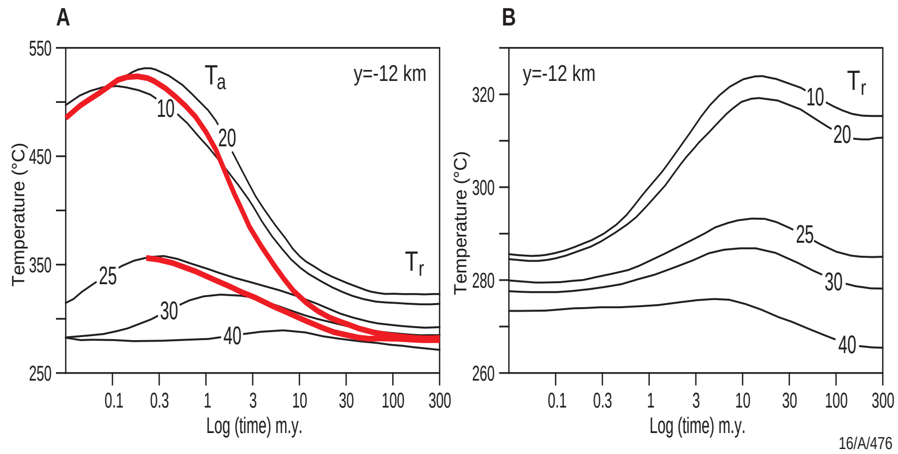

Fig. 24 ***(centre left).*** **Temperature–time paths for the thermal model. Each path corresponds to a depth (y) of 12 km (adjacent to the heat-production maximum) and to points at lateral distances of 10, 20, 25, 30 and 40 km, as labelled, from the centre of the granite. Parameters are shown in Figure 23.** ***(A)*** **Both the thermal anomaly due to advective heat associated with intrusion (Ta) and subsequent radiogenic heating (Tr) associated with 'typical' Mesoproterozoic granite. The advective thermal anomaly (in the absence of any additional radiogenic heating component) is also shown (in red) for the 20- and 25-km temperature–time-path sites. This advective thermal anomaly is sustained for only ~3 m.y. after intrusion, and is not recorded in rocks more than ~5 km from the pluton margin (as indicated by the difference between the 25- and 30-km paths).** ***(B)*** **The radiogenic thermal anomaly (ignoring the initial advective response) shows a 30–40°C increase in temperature from that which would result from advective heat alone. Heating due to radiogenic decay reaches a maximum ~10 m.y. after intrusion, but is sustained well above the background temperatures for up to 300 m.y. (note logarithmic scale). The long-term cooling apparent some distance away from the intrusion (i.e., 40-km path) is a result of the upward movement of heat-producing elements from the source into the intrusion. This effect contributes to elevated lateral thermal gradients which may promote fluid circulation.**

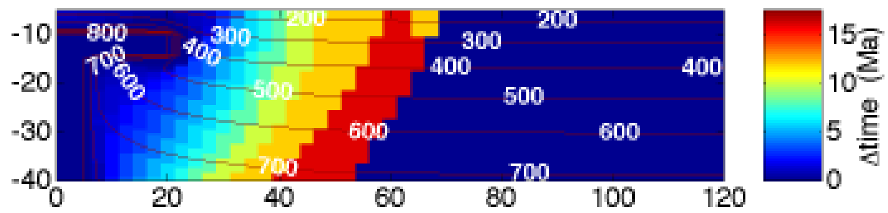

Fig. 25. Model x–y section contoured for temperature and also for the time (in m.y.) post-intrusion that various sections of the crustal column attain their maximum temperature. For example, the granitic body itself attains maximum temperature at the time of intrusion (Δtime = 0 m.y.). At a distance of 10–20 km from the pluton margin, however, maximum temperatures are not attained until 5–10 m.y. after intrusion; this is the result of the additional phase of heating caused by radiogenic decay (Tr).