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Tectonic constraints on the timing relationships of metamorphism, fluid production and gold-bearing quartz vein emplacement

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Abstract

There is an ongoing discussion about the genetic significance of the postmetamorphic emplacement of many gold mineralizations. As a contribution to this discussion, this paper reviews the timing relationships between metamorphic devolatilization and metamorphism at different crustal levels for different tectonic processes. For example, denudation accompanying or following thickening causes metamorphism to occur later at depth than at shallow levels. Thus, many internally-heated terrains (e.g. Barrovian terrains) are of 'deep-later' type; that is, peak metamorphism (and devolatilization) at deeper levels occurs at later times. Metamorphic processes of the 'deep-later' type may produce and release metamorphic fluids during prograde metamorphism at depth and precipitate them in the form of 'postmetamorphic' quartz veins at shallow levels.

Magmatic heating from below, on the other hand, is a 'deep-earlier' process causing inverse timing relationships. In many metamorphic terrains deep-later and deep-earlier processes may compete, for example if denudation at the surface accompanies heating from below. If denudation and heating from below are of similar duration, 'deep-later' characteristics prevail and a strongly bi-modal age distribution of peak metamorphism in different crustal levels may arise: the upper crust will experience metamorphism early but largely contemporaneously and the lower crust will experience metamorphism much later. This process is particularly favourable for substantial simultaneous devolatilization of large sections of the lower crust to postdate metamorphism at shallow levels. Thus, such processes may result in late infiltration 'events' in cooling rocks of low metamorphic grade. The common observation of postmetamorphic fluid infiltration and mineralization may therefore indicate, but does not require, that the mineralising fluids are related to the same metamorphic event.

Keywords: lode-gold mineralisation; timing relationships; postmetamorphic; devolatilisation; thermal evolution

1. Introduction

Explaining the relative and absolute timing relationships of different geological processes involved with the formation of gold deposits plays an important role in our understanding of their nature (see Keppie et al., 1986; Ho and Groves, 1988; Ho and Groves, 1989; Arne et al., 1998; Foster et al., 1998). Many gold–lode deposits of all ages share intriguing and characteristic timing relationships between: (1) metamorphism of the host rocks; (2) gold-bearing vein emplacement; and, if granitoids are present, (3) granitoid emplacement (Table 1).

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Table 1
Timing relationships in some important gold producing provinces hosted by greenschist facies metamorphic rocks. $\Delta t_{(fl)}$ is the time gap between metamorphism and infiltration by the mineralizing fluids. $\Delta t_{(intr)}$ is the time gap between metamorphism of the greenschist facies host rocks and granitic intrusion (if present)

Province	Age	$\Delta t_{(intr.)}$	$\Delta t_{(fl.)}$	Reference
Meguma, NS, Canada	Devonian	≈ 30 m.y.	≈ 30–40 m.y.	Kontak et al., 1990
Victorian Slate Belt, Australia	Devonian	≈ 10–30 m.y.	≈ 30 m.y.	Wilson et al., 1992; Arne et al., 1998; Foster et al., 1998
Superior Province, Ont., Canada	Archaean	≈ 10–20 m.y.	≈ 20–50 m.y.	Card et al., 1989; Jamielita et al., 1990
Yilgarn Block, Western Australia	Archaean	≈ 20–50 m.y.	≈ < 50 m.y.	Groves et al., 1989
Valdez Group, Alaska	Tertiary	≈ < 10 m.y.	≈ < 10 m.y.	Haeussler et al., 1995; Goldfarb et al., 1986
Otago Schist, New Zealand	Tertiary	NA	≈ 20 m.y.	Koons and Craw, 1991

These relationships include: (1) Quartz vein emplacement and gold mineralization postdate metamorphism of the immediate host rocks and a characteristic hiatus of some tens of millions of years occurs between metamorphism and mineralization (e.g. Steed and Morris, 1986; Jamielita et al., 1990; Wilson et al., 1992) (Table 1; Fig. 1). (2) Mineralization occurred during cooling of the host rocks through the brittle–ductile transition. (3) Mineralization may be closely related in time to the emplacement of granitoids. In addition, many of these deposits are restricted to mid-greenschist metamorphic rocks and are absent from higher or lower grade rocks (e.g. Goldfarb et al., 1986); they show a spatial association with granitoid intrusions and are characterized by low-salinity fluids (Phillips and Powell, 1993).

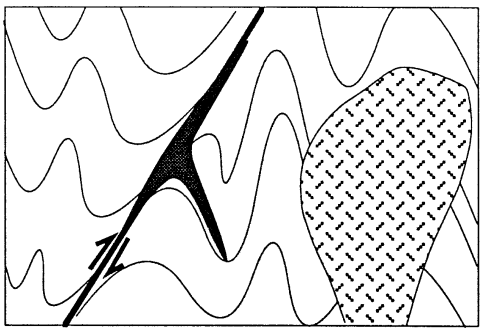

Fig. 1. Cartoon summarizing typical timing and spatial relationships of many mesothermal gold deposits on the example of the central Victorian gold deposits, Australia. The characteristic 'saddle reef' structure of the Victorian gold deposits including part of the reef in the 'saddle' of an anticline and part of the reef along a reverse fault (black area) indicates emplacement during the brittle ductile transition of the deforming host rocks. Granites are generally undeformed (cross hatched area) indicating emplacement after, or in the late stages of, deformation.

Observations that veins postdate metamorphism of the immediate host rocks have been used to argue that the mineralising fluids are unrelated to metamorphism of the host rocks (Jamielita et al., 1990) or to support 'magmatic models' (e.g. Campbell and Hill, 1988). In examples where geochemical criteria indicate a metamorphic origin of the mineralising fluids (e.g. Phillips and Groves, 1983), models have been designed to explain relatively long-term retainment of devolatilized fluids in the metamorphic pile before precipitation (e.g. Goldfarb et al., 1986; Groves et al., 1988). However, an increasing awareness about the timing of metamorphism in different crustal levels of orogenic belts has highlighted that this argument is not always necessary (e.g. Sandiford and Keays, 1986; Powell et al., 1991; Phillips and Powell, 1993; Stüwe et al., 1993). Different crustal levels may experience metamorphism at different times. Thus, fluid release at some crustal levels may correspond to the time of retrograde metamorphism and vein emplacement elsewhere in the pile.

Stüwe et al. (1993) have shown that, depending on the tectonic environment, prograde metamorphism and fluid production at depth may occur up to several tens of million years after mid-greenschist metamorphic rocks at shallow crustal levels reached their metamorphic peak. Stüwe et al. (1993) also showed that the duration of an observed hiatus between host-rock metamorphism and vein emplacement may be used to infer some aspects of the underlying tectonic process, in particular if further geological observations like the timing of granitoid emplacement help to constrain the sequence of thermal events. They concluded that the relative timing of vein emplacement to metamorphism is mainly a function of the timing of onset of denudation in a region.

This study reviews the characteristic timing relationships between prograde and retrograde metamorphism at different crustal levels for a series of tectonic environments. The relationships between these timing characteristics and metamorphic grade are highlighted. Implications of different timing relationships for the emplacement of mineralised quartz veins are discussed.

1.1. Assumptions

In the discussion presented below, the following assumptions are made: (1) Prograde metamorphism will produce and release metamorphic fluids by breakdown of hydrous minerals. (2) These fluids travel in the direction of the principle pressure gradient, that is upwards, in the metamorphic pile. (3) The rate of fluid flow is rapid compared to the rate of temperature change. Thus, fluids released at depth can be assumed to precipitate vein material practically simultaneously at higher crustal levels. Heating and cooling are assumed to be the principle factors controlling fluid release and vein precipitation (Manning, 1994) and the influence of the pressure field is neglected. The use of 'prograde' will refer to 'up temperature' and 'retrograde' to 'cooling'. 'Metamorphic peak' refers to the maximum temperature. Note also that 'increasing' or 'decreasing' time refers to the time after onset of an event. Thus, increasing time refers to decreasing age as may be inferred by geochronology.

Clearly, some of the considerations presented below rely on these assumptions, in particular the direction of fluid flow and the assumption of a one-dimensional geometry of the thermal process. Because of these gross over-simplifications, quantitative application of the models discussed herein is limited. For example, the reader is reminded of the comparably small fluid fluxes that can be attained by devolatilization alone and therefore the necessary focusing mechanisms for metamorphic quartz vein formation (e.g. Connolly, 1997; Thompson, 1997 and references therein). Regardless, the assumptions are plausible for many scenarios and they are justified inasmuch as it is the aim of this contribution to outline possible timing relationships.

1.2. Deep-later versus deep-earlier

In order to discriminate between tectonic environments that produce pre- or postmetamorphic peak quartz veining by devolatilization elsewhere in the metamorphic pile, we distinguish between metamorphic processes with 'deep-later' characteristics and metamorphic processes with 'deep-earlier' characteristics (Fig. 2). In the former, peak metamorphism at deep levels occurs later than at shallow levels, in the latter these timing relationships are reversed. Thus, in deep later areas, prograde devolatilization may well be active during retrogression of rocks at shallower levels. However, these relationships have no implications about the change of metamorphic grade with depth. Thus, deep-earlier and deep-later characteristics may both be accompanied by either grade increase or grade decrease with time. Which relationship exists is a good indication of the heating mechanism and therefore of the tectonic environment.

The function that may best be used to describe vertical timing (and grade) relationships of metamorphism is the piezothermal array (Fig. 2). England

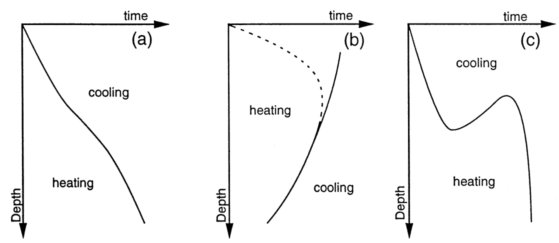

Fig. 2. Different possible timing relationships between metamorphism at different crustal levels. The curves show the time of peak metamorphism (piezothermal arrays), so that depth-time paths of rocks on the left-hand side of the curves are prograde (heating) and depth-time paths on the right-hand side of these curves are retrograde (cooling). (a) shows a piezothermal array of the 'deep-later' type which occurs if heating is slow compared to the rate of denudation at the surface, as for example in Barrovian terrains. (b) shows an example of 'deep-earlier' relationships which may occur during heating from below. However, the theoretical 'deep-earlier' (and shallow-later) relationship is limited in reality by the constraint that the surface cannot change its temperature (dashed part of piezothermal array). Thus, deep-earlier relationships due to processes like underplating are probably limited to the lower crust. (c) If heating from below is of a similar time scale to denudation from above, 'deep-earlier' and 'deep-later' characteristics compete and strongly-curved piezothermal arrays may occur. This shape implies a bi-modal age distribution of metamorphism and may by particularly favorable for postmetamorphic fluid infiltration events.

and Thompson (1984) defined the piezothermal array as the line that connects the metamorphic temperature peaks of all crustal levels through time. Corresponding to this definition, piezothermal arrays with a positive slope in depth-time space correspond to ‘deep-later’ characteristics and with a negative slope to ‘deep-earlier’ characteristics. The slope of this function is therefore a crucial parameter in the discussion of the timing of quartz veining with respect to the metamorphic peak of the host rocks. Much of the discussion below will focus on the slope of this function in time-depth space.

2. Timing relationships in different tectonic environments

The timing relationships between metamorphism at different crustal levels depend on (a) the heating mechanism and (b) the processes at the boundaries of the crust. This section discusses the timing relationships for a series of boundary conditions and heating mechanisms as they have been used in well-accepted models for some tectonic environments. The implications of these timing relationships for the timing of the release and emplacement of fluids will then be discussed in a later section.

2.1. Timing relationships due to internal heating

During and following crustal thickening, metamorphism is caused by (a) burial of the rocks to deeper crustal levels and (b) increased radiogenic heat production in the thickened pile. Thus, regions that experienced this type of metamorphism are often referred to as ‘internally-heated’ or ‘Barrovian’ terrains. These terrains typically reach maximum temperatures consistent with upper greenschist and amphibolite facies conditions, following maximum geothermal gradients of around, or less than, 30°C/km. Crustal thickening in itself provides no mechanism for cooling and no retrograde metamorphism can therefore be achieved during or following crustal thickening alone (dashed lines Fig. 3a). However, thickened continental crust is inherently unstable and crustal thinning by erosion or extensional denudation is likely to accompany and follow thickening. During this process, the cooling effects of exhumation compete with the heating effects of internal heating.

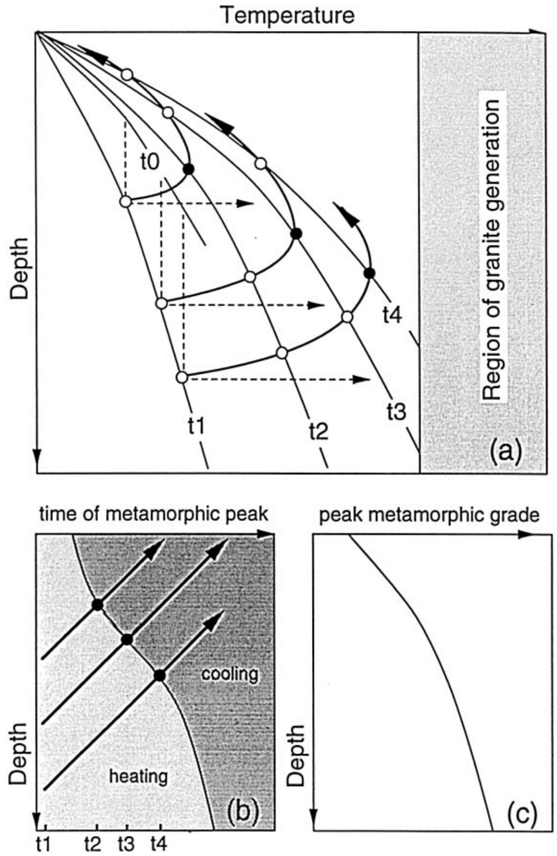

Fig. 3. Timing relationships in internally-heated terrains. (a) Depth–temperature ($z-T$) paths for three different depths (thick solid lines) and geotherms for four different time steps ($t1-t4$, thin solid lines) are shown. Dashed lines are $z-T$ paths if no erosion was present. White circles denote different time steps of the $z-T$ paths. Black dots show metamorphic peak depth, temperature and time. The piezothermal array is given by the locus of the black dots. (b) Piezothermal array (thin solid line) separating depth–time space into a prograde region (light shading) and a retrograde region (dark shading). Depth–time paths of three different rocks corresponding to those in (a) are also shown. (c) Relationship between peak metamorphic grade and depth.

England and Richardson (1978) recognised that the similar time scales of crustal-scale denudation and thermal equilibration give rise to characteristic depth–temperature paths that have a ‘clockwise’ sense in a diagram with pressure increasing upwards and temperature increasing to the right. (Note that, whereas the term ‘clockwise’ is commonly used for these depth–temperature paths, they are anticlockwise in Fig. 3a where the depth axis is drawn downwards). Because shallower level rocks 'feel' the effects of the denuding and cooling surface earlier than deep level rocks, these processes give rise to a piezothermal array with a uniformly positive slope. That is, $\mathrm{d}z/\mathrm{d}t|_{T=T_{max}}$ is always larger than zero; peak-metamorphism occurs later at depth than at shallow levels (Fig. 3b).

The relationship of time of metamorphism to grade of metamorphism is given by the shape of the geotherms (Fig. 3a) and a comparison of Fig. 3b and c. Geotherms during internal heating increase in temperature with depth during all time steps. Thus, metamorphic grade increases with the time of peak metamorphism. Rocks with older metamorphic ages will be of lower grade and rocks with younger metamorphic ages of higher grade.

The temporal relationships between metamorphism and deformation are illustrated by considering the cause of metamorphism. In internally-heated terrains, metamorphism is ultimately caused by crustal thickening during deformation. Metamorphism following thickening relies on heat conduction across the lithosphere. The duration of thermal equilibration, as expressed by the thermal time constant of the crust, is of the order of several tens of million years. Thus, metamorphism will occur only some tens of million of years after initial thickening and there is a substantial hiatus between deformation and initial metamorphism.

2.2. Timing relationships due to external heating

Terrains heated by magmatic underplating from below or by magmatic intrusion in the middle crust are often referred to as 'externally-heated' or 'advectively-heated' terrains (Jaeger, 1964; Lux et al., 1986; Barton and Hanson, 1989). Underplating and mid-crustal magma emplacement may also be coupled (Huppert and Sparks, 1988). Depending on the crustal level of magma emplacement, the metamorphic T/depth ratios may greatly exceed those of Barrovian metamorphism and may reach more than 50°C/km. Regardless of the level of magma emplacement, time of metamorphism increases with distance from the heat source (Fig. 4a and b) and metamorphic grade decreases with distance from the heat source (Fig. 4c; denTex, 1963; Wells, 1980). Thus, unlike internally-heated terrains, highest metamorphic grades at depth are reached earlier than low metamorphic grades at shallower levels. Externally-heated terrains are of the 'deep-earlier' type and grade decreases with increasing metamorphic age. For extremely simplifying assumptions, externally-heated terrains may be described with an analytical solution of the heat flow equation (Jaeger, 1964). An example of such a quantitative prediction of these timing relationships is given in the Appendix A and in Fig. 5. There, the piezothermal array is strictly 'deep-earlier' because there is no top boundary. It is

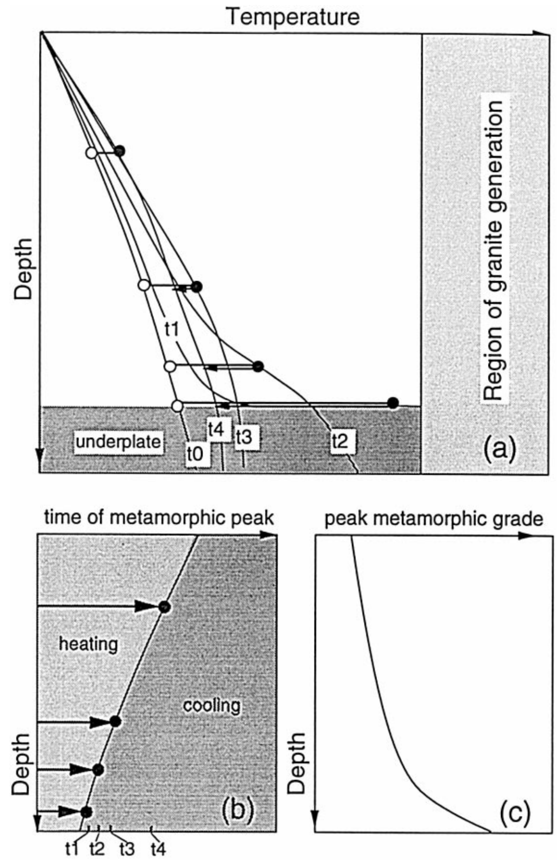

Fig. 4. Timing relationships in terrains heated from below with no erosion. (a) Depth–temperature paths (thick solid lines) and geotherms (thin solid lines). Black dots show metamorphic peak depth, temperature and time. (b) Piezothermal array (thin solid line) in depth–time space and depth–time paths of four different rocks corresponding to those in (a). (c) Relationship between peak metamorphic grade and depth.

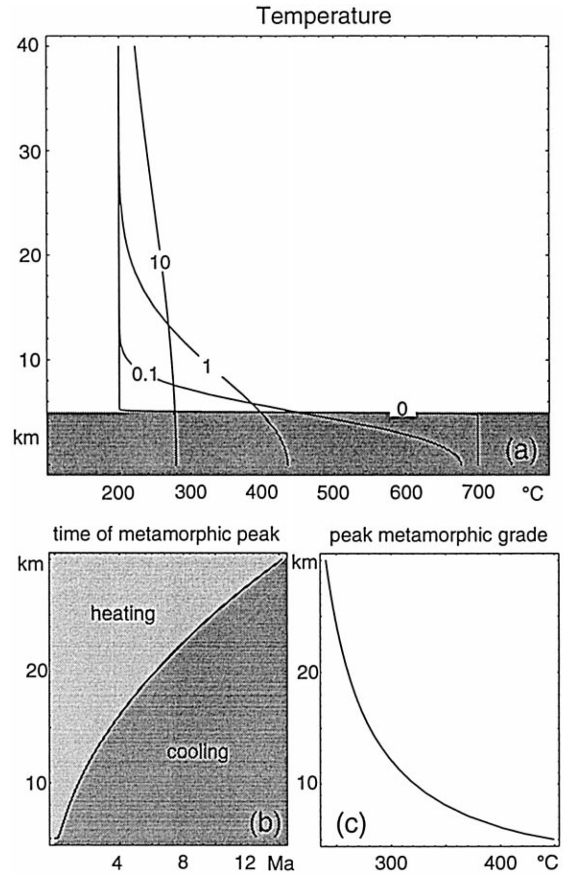

Fig. 5. Calculated timing relationships that arise due to the thermal relaxation of a one-dimensional step-shaped temperature distribution of 10 km thickness and 700°C 'intrusion temperature' into 200°C host rocks. Temperature profiles shown in (a) are contoured for m.y. (b) shows the piezothermal array, (c) shows the peak metamorphic temperature. Compare directly with the qualitative diagram of Fig. 4. The difference in curvature of the piezothermal array between Fig. 4 and Fig. 5 is irrelevant for the argument presented here. Distances are in kilometers from the center of the sill-shaped 'intrusion'.

assumed that the heat source is emplaced in an infinite medium; that is, the magma is emplaced at very large distances from the surface. In realistic examples, the 'deep-earlier' characteristics of externally-heated terrains are limited by the requirement that the surface cannot change temperature (Fig. 2b). Thus, whereas external heating is a 'deep-earlier' type process, externally-heated terrains are usually not of strictly 'deep-earlier' type, but are characterised by curved piezothermal arrays which are only 'deep-earlier' in their high-grade part (Fig. 2b, dashed curve).

Metamorphism and deformation are intimately coupled in externally-heated terrains. If far field stresses control deformation in an orogen, then external heating may weaken the crust so that appreciable deformation takes place (e.g. Sandiford et al., 1991). Thus, in externally-heated terrains deformation may be seen as the consequence of metamorphism and is likely to occur simultaneously with metamorphism. Cause and consequence of metamorphism and defor-

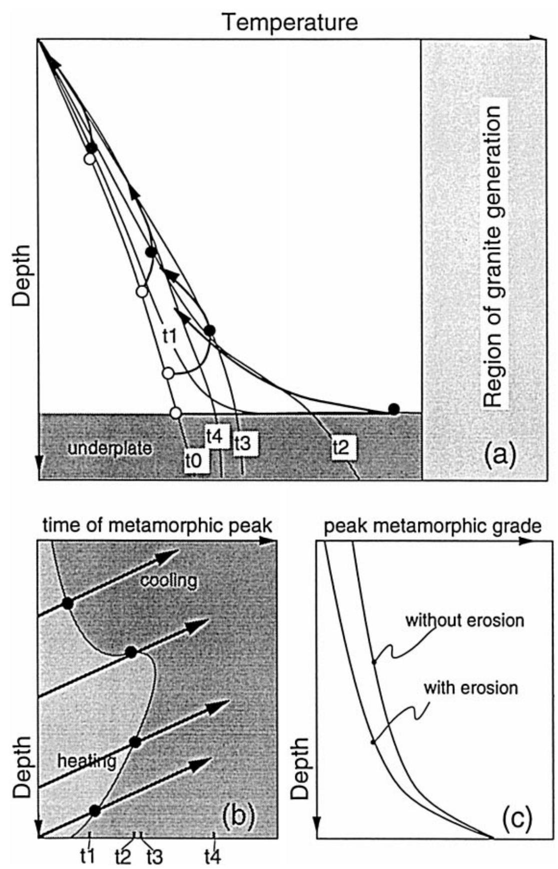

Fig. 6. Timing relationships in terrains heated from below and eroding at the surface. (a) Depth–temperature paths (thick solid lines) and geotherms (thin solid lines). Black dots show metamorphic peak depth, temperature and time. (b) Piezothermal array (thin solid line) in depth–time space and depth–time paths of four different rocks corresponding to those in (a). (c) Relationship between peak metamorphic grade and depth. The relationship in (c) is also shown for the erosion-absent case, for direct comparison with Fig. 4.

mation are therefore reversed in externally-heated terrains from internally-heated terrains.

2.3. Timing relationships during contemporaneous external heating and denudation

Underplating or substantial inflation of the crust by magmatic intrusion may result in tectonic uplift of the surface and subsequent erosion. Akin to the effect of erosion in internally-heated terrains, erosion will cause cooling from above, with the effects of cooling being successively later at deeper levels (Fig. 4a and b). Thus, terrains that are heated from below and erode at the surface have 'deep-later' characteristics caused by cooling at the surface competing with 'deep-earlier' characteristics caused by heating from below (Fig. 6a). The competition of the two processes will cause a very pronounced S-shape of the piezothermal array (Fig. 6b). A bi-modal age distribution of peak metamorphism may arise: shallow levels may reach their metamorphic peak early and deep levels may reach their metamorphic peak later. It is possible that a singularity in the age distribution arises so that only very early and very late metamorphic ages are possible and no intermediate ages exist (Stüwe et al., 1993). Corresponding to this shape of the piezothermal array, metamorphic grade will increase with metamorphic age at deep levels, but decrease with increasing metamorphic age at shallow levels.

3. Implications for the timing of fluid passage and gold mineralisation

Heating from below causes 'deep-earlier' type metamorphism. Metamorphic fluids released during prograde devolatilization at depth may therefore infiltrate shallow levels that are on their prograde path. If these fluids precipitate quartz veins at shallow levels, then such veins may be remobilized during subsequent prograde metamorphism, or may be preserved as 'early' quartz veins in the sequence. However, heating from below alone is unlikely to be responsible for postmetamorphic fluid infiltration unless other processes operate to preserve the fluids in the rocks prior to their precipitation.

Internal heating processes, on the other hand, may produce fluids at depth, while shallower levels are on their retrograde path. If these fluids travel upwards in the pile and precipitate vein material in cooling rocks at shallow levels, they may, in principle, cause postmetamorphic quartz veining and possibly mineralization. In strictly 'deep-later' type metamorphic processes, for example that of Barrovian-type metamorphism, the time of metamorphism increases continuously with depth (Fig. 2a and Fig. 3b). Thus, all crustal levels experience metamorphism at different times and reach their metamorphic peak at different times. As a consequence, there is no specific time at which there is a maximum in fluid production. During the entire cooling history of shallow crustal levels, there is always prograde metamorphism at depth and a prolonged history of prograde devolatilization at depth is likely. Such processes favour therefore postmetamorphic quartz veining but may not allow the substantial concentration of fluid infiltration into a single event. Regardless, the time difference between prograde metamorphism at shallow and deep levels is plausibly as large as 50 m.y. (Stüwe et al., 1993). This allows thermal and infiltration processes over a period of 50 m.y. to be explained within a single metamorphic process. This interpretation invalidates the argument that postmetamorphic quartz veins cannot be produced by metamorphic devolatilization (e.g. Campbell and Hill, 1988; Jamielita et al., 1990).

If cooling from above is of a similar time scale to a thermal cycle at the base of the crust, as may be the case for contemporaneous denudation and heating from below, the piezothermal array will be strongly S-shaped (Fig. 2c and Fig. 6b). This S-shape implies a bi-modal age distribution of metamorphism with shallow level rocks attaining peak metamorphism early (but contemporaneously) and deep level rocks attaining metamorphism much later (but contemporaneously). The fact that large vertical sections of the lower crust may experience metamorphism simultaneously, but much later than the upper crust, has important implications for fluid infiltration. Fluid producing reactions, for example the breakdown reactions of micas and chlorites, will be met by large parts of the lower crust at the same time. Contemporaneous devolatilization in many rocks may cause a fluid infiltration 'event' in others. If fluids migrate upwards, then these fluids may cause an infiltration 'event' in greenschist facies metamorphic rocks that experienced their metamorphic peak much earlier.

It is therefore suggested here, that environments in which heating from below is coupled with minor denudation at the surface are particularly favourable for the occurrence of a 'postmetamorphic' fluid infiltration event in which the fluids are derived from prograde metamorphism at depth, but belonging to the same event. Such a tectonic environment has been suggested from independent evidence for several auriferous provinces, for example the Lachlan fold belt (Looseveld and Etheridge, 1990) and the Yilgarn Block of Western Australia (e.g. Powell et al., 1991).

4. Discussion

The discussion above has shown that the vertical timing relationships between metamorphism at different crustal levels are predominantly a function of the absolute time scale and the relative timing of the thermal processes at the top and bottom boundaries of the crust. If a thermal cycle of the base of the crust is rapid, as for example during and following the emplacement of an underplate, and if denudation is slow, then 'deep-earlier' characteristics will prevail. If, on the other hand, the thermal cycle at the base of the crust is slow, as may be an appropriate description of internal heating of the crust, and if denudation is rapid or sets on early in the thermal evolution, then 'deep-later' characteristics will dominate the timing relationships. If the duration of the thermal cycle at the base of the crust is of the same order as the denudation, then deep-earlier and deep-later characteristics compete and piezothermal arrays with strong S-shapes will form. The duration of both processes must be of the order of several tens of million years so that their thermal consequences are 'felt' over the entire crust.

The difference between strictly 'deep-later' metamorphic processes in which time of metamorphism increases more or less continuously with depth (e.g. Barrovian metamorphism; Fig. 2a) and metamorphic 'deep-later' metamorphic processes with a strongly bi-modal age distribution of metamorphism (Fig. 2c) may have important implications for the presence of gold deposits in a metamorphic terrain. The former produces metamorphic fluids throughout the orogenic cycle. These fluids may be emplaced at shallow levels during a prolonged period of fluid infiltration and quartz vein formation. Because of the prolonged duration of the infiltration process, focusing of very low fluid fluxes may be difficult and dispersion of the fluids relatively easy. The latter process, on the other hand, causes a single late stage fluid infiltration event and may therefore be more favourable for the concentration of fluids into an auriferous province.

Other linkages between different post metamorphic mineralizations may help to constrain this interpretation. For example, a close temporal and spatial association of S-type granitoids with gold mineralization is often observed in the field. This may indicate that the time of substantial metamorphic devolatilization coincides with the time of partial melting in the lower crust. Thermal models including denudation at the surface and scaled to produce partial melting in the lower crust near the time of maximum devolatilization (Stüwe et al., 1993) show that rocks now at the surface will have been at mid-greenschist facies during the infiltration event. This modelling result is well-matched by observations about the distribution of gold deposits in some auriferous provinces with metamorphic grade (e.g. Goldfarb et al., 1986).

5. Conclusion

Simple qualitative consideration of the timing relationships between metamorphism at different crustal levels shows that:

Internal heating processes are characterised by 'deep-later' type relationships. Therefore, in Barrovian terrains, lower crustal levels may experience peak metamorphism much later than shallow crustal levels. External heating from below, on the other hand, is characterised by 'deep-earlier' relationships. Metamorphic fluids may be released by prograde devolatilization at depth and travel upwards to precipitate vein material at shallow levels. Depending on the vertical timing relationships and therefore on the tectonic environment this may cause either pre- or postmetamorphic quartz veining. Postmetamorphic infiltration can be related to prograde devolatilization at depth during the same thermal event, if the hiatus between metamorphism and vein emplacement is less than about 50 m.y.

In tectonic environments where heating from below is accompanied by denudation at the surface 'deep-earlier' and 'deep-later' processes compete and bi-modal peak metamorphic age distributions may arise. The upper crust may experience early but contemporaneous metamorphism and the lower crust may experience metamorphism also contemporaneously but much later. Such processes are particularly favourable for substantial event-like fluid release at depth and emplacement in retrograde rocks at shallower levels. Interestingly, such processes have been suggested as the tectonic environment for some auriferous provinces, for example the Lachlan Fold belt of eastern Australia or the Archaean gold deposits of Western Australia.

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Appendix A

The timing relationships due to external heating processes may be predicted by a simple consideration of an analytical solution of the diffusion equation for the boundary and initial conditions:

- $T = T_i$ in the region $-D/2 < z < D/2$ and $T = T_b$ in the region $-D/2 > z > D/2$ at time $t = 0$,
- $T = T_b$ at the positions $z = +\infty$ and $z = -\infty$ at $t > 0$.

where T_i is the intrusion temperature, T_b is the hostrock temperature, κ is the thermal diffusivity (assumed to be 10^{-6} m^2 s^{-1}), D is the thickness of the intrusion and z is the distance from its center (Jaeger, 1964). These conditions describe the thermal relaxation of an initially step-shaped temperature distribution, as appropriate for the description of cooling sills, for example an underplate. The solution is given by:

$$T = T_b + \left(\frac{T_i - T_b}{2}\right)\left(\operatorname{erf}\left(\frac{0.5D - z}{\sqrt{4\kappa t}}\right) + \operatorname{erf}\left(\frac{0.5D + z}{\sqrt{4\kappa t}}\right)\right) \quad (A.1)$$

(Carslaw and Jaeger, 1959). The time of the metamorphic peak is found by differentiating this solution with respect to t and setting zero to give:

$$t_{T_{max}} = -\frac{zD}{2\kappa \ln((z - 0.5D)/(z + 0.5D))} \quad (A.2)$$

Fig. 5 shows temperature profiles, time and grade of the metamorphic peak as functions of distance from the underplate for direct comparison with Fig. 4. The different curvatures of the peak time function in Fig. 4b and Fig. 5b arises from different boundary conditions. However, importantly, both curves have the same slope.

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