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ARTICLE

Preferential magma extraction from K- and metal-enriched source regions in the crust

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Abstract We compare melting of potassic alteration zones in metamorphosed gold deposits with that of unaltered rocks of the same protolith to examine their relative contributions to crust-derived magmas and to investigate the implications for ore genesis. Potassic hydrothermal alteration, at the crustal levels where orogenic gold deposits form, stabilizes a higher proportion of muscovite and biotite than is possible in unaltered rocks at high metamorphic grades. Because these micas contain water, they control the melt fraction generated through dehydration melting in that a greater proportion of micas permits more extensive melting. Orogenic gold deposits, in which mineralization is typically encapsulated by potassic alteration, form at deep-enough crustal levels to survive repeated tectonic activity, which can lead to their being metamorphosed. In the vicinity of this metamorphosed gold mineralization, the greatest proportion of felsic melt is generated in the more metal- and sulfur-rich rocks because of the associated potassic alteration. Ore minerals dissolve and are physically incorporated into the resulting felsic melt, which thereby becomes metal- and sulfur-enriched. Since melt fraction is the dominant control on strain partitioning and melt mobilization, increased melting in K-altered mineralized rocks implies that these sites will be the first to experience melt escape and will continue to be the focus of melt escape during ongoing metamorphism. This strain partitioning promotes shear zone development, and once shearing is localized to K-altered mineralized domains, it may attract external magma, allowing extension and linking with nearby active shear zones. In this way, mineralized zones may connect to a regional network of magma transfer, allowing metal enrichment of migrating magmas. Terrains that underwent widespread K alteration associated with mid-crustal gold enrichment are likely, when metamorphosed, to produce significant volumes of reduced, relatively metal- and sulfur-enriched felsic magma. The ages and relative tectonic preservation potential of different K alteration-associated ore types implies that Au, Ag, As, Sb, Bi, Te, and W may be recycled within the crust through this mechanism, whereas Cu and Mo are unlikely to be recycled and require mantle sourcing to form new intrusion-related ores. Silicate melt derived from preexisting zones of gold enrichment in the lower crust may contribute significantly to the metal budget of intrusion-related gold systems, and possibly some gold-rich porphyry deposits.

Keywords Ore genesis · Source · Anatexis · Granite metallogeny · Intrusion-related gold

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Introduction

Felsic magma-related ore deposits are Earth's largest source of copper, molybdenum, tin, tungsten, and a major source of gold. At the broadest scale, some continental-scale regions contain many felsic magma-related ore deposits, whereas others are relatively barren. Even within rich provinces, a few intrusions are associated with mineralization, and the majority are barren. It is likely that there are several explanations for these observations, and one of these may be variability in the magma source. Yet, there have been a few studies of processes that affect metal distribution in magma source regions.

Various suggestions have been offered for the source of metals in felsic magma-related ore deposits. Some suggest that in arc regions, metal is derived from subducted oceanic slab or overlying metasomatized mantle wedge (Mungall 2002; Sillitoe 1997), remnant metallogenic heterogeneities in the mantle (Sillitoe 1972), adjacent intruded crust (Krauskopf 1967), or from the lower crust during anatexis (Hedenquist and Lowenstern 1994; Tomkins and Mavrogenes 2003). Intrusion-related gold systems form distally to arcs and are typically associated with reduced granitic magmas thought to be largely derived from partial melting of crustal rocks (Lang and Baker 2001), casting into question the absolute need for oceanic slab or mantle involvement. Even within arcs, evolution of ore-producing magmas may involve mixing between mantle- and crust-derived magmas (Richards 2003). It is therefore crucial to understand processes that influence the metal content of these crust-derived magmas.

This paper investigates differences in the proportions of magma produced through dehydration melting of rocks previously subjected to potassic hydrothermal alteration compared to unaltered rocks of the same protolith. Many of these altered rocks are metal-enriched, and the results therefore have implications for the metal content of crust-derived melts. Pseudosections calculated with the thermodynamic program THERMOCALC are used to model differences in melt production for both a pristine unmetamorphosed gold deposit, with associated K alteration, and a gold deposit metamorphosed at granulite facies conditions, where differences in melt production can be observed. Linking this information with an understanding of melt extraction dynamics allows an assessment of the role of crust-derived magmas in generation of intrusion-related ore systems in the upper crust.

K-metasomatism and associated metal enrichment

There are many different environments where rocks can be subject to addition of potassium via hydrothermal fluids. Most types of ore deposits associated with felsic magmas have an attendant K-alteration signature, including (1) greisen-hosted Sn–W–Mo deposits, (2) porphyry Cu±Au±Mo deposits, (3) IOCG deposits, and (4) many intrusion-related Au systems. Orogenic gold deposits are also almost invariably characterized by potassic alteration and formed periodically throughout Earth history, mainly during the Archean and Phanerozoic (Groves et al. 2005).

Other processes unrelated to metal enrichment can also lead to formation of zones of K enrichment within the crust. Diagenesis can, in some cases, promote localized K enrichment, and weathering can also lead to localized enrichment in potassic clays. Deeper within the crust, fault zones, as well as broad shear zones, are the focus of fluid flow, and this allows some of these regions to become K-enriched. The Broken Hill Block in western New South Wales contains examples of this shear zone K-enrichment. At this locality, there are many broad Delamerian aged (490–514 Ma; Rutherford et al. 2006) shear zones with lithologies that are significantly more muscovite- and biotite-rich than their unaffected protoliths. These processes create some of the natural variability in the fertility of rocks that is a characteristic of any broad crustal region.

Because most felsic magma-associated ore deposit types form at shallow crustal levels in zones of crustal thickening and high topographic relief, they have a high probability of being removed by erosion shortly after they form. For example, most of the currently mined giant porphyry Cu deposits are <50 My old and were actively being eroded when found. In contrast, the numerous Archean orogenic gold deposits were able to survive the weathering process for much longer because they formed at deeper crustal levels. Thus, orogenic gold deposits have significantly higher tectonic preservation potential than porphyry Cu deposits. Since some intrusion-related gold systems and intrusion-associated Sn–W deposits form at slightly deeper crustal levels than porphyry Cu deposits (e.g., Baker 2002), they have higher preservation potentials. However, most of these deposits are Phanerozoic in age (Seedorf et al. 2005; Cerny et al. 2005; Lang and Baker 2001) and, thus, have not had time to form, stabilize, and then be tectonically emplaced into a position in which they can be metamorphosed. We have therefore focused on metamorphism of orogenic Au deposits because these have a greater probability of being preserved and later metamorphosed than other deposit types.

Orogenic gold deposits form through migration of metamorphic fluids through shear zones and are typically associated with second- or third-order faults connected to large crustal-scale shear zones (Groves et al. 1998). Ore minerals found within these deposits are, in addition to gold, dominated by pyrite, pyrrhotite, and arsenopyrite, but minor and varying amounts of tellurides, bismuthinides, chalcopyrite, stibnite, sphalerite, galena, and scheelite can be present. Groves et al. (1998) indicate that most orogenic gold deposits are characterized by addition of S, K, H_2O, and CO_2, and in some, Na, Ca, and LILE, to host rocks ranging from mafic rocks (most Archean deposits) to pelitic and psammitic turbidites (most post-Archean deposits). Potassic alteration in these deposits typically results in formation of new muscovite and biotite, depending partly on the bulk composition of the altered protolith and the degree of alteration (e.g., White et al. 2003), although K-feldspar is found in some deposits thought to have formed under amphibolite facies conditions (Ridley et al. 2000). The majority orogenic gold deposits formed at 300±50°C and 1–3 kbar, although some formed at conditions up to 450–600°C and 3–5 kbar (Groves et al. 1998).

Retention of water within metasomatized rocks will be shown below to be a critical control on the proportion of melt generated during subsequent metamorphism. Water is retained within micas, clays, and chlorite, so the amount of K added partly controls the proportion of H_2O retained within the rock. Note that potassic alteration that is dominated by formation of K-feldspar rather than muscovite does not favor retention of H_2O. Most added cations are preserved within the altered volume during subsequent metamorphism up to mid-amphibolite facies conditions, as biotite, muscovite, and feldspars are stable at these conditions. Breakdown of clay-bearing alteration assemblages in the greenschist facies will lead to H_2O loss, although some will be retained within newly formed phyllosilicate minerals. In chlorite- and carbonate-bearing rocks, some H_2O may be lost upon conversion of chlorite to hornblende, biotite, or other Fe–Mg silicates at the greenschist–amphibolite facies transition, and CO_2 is lost through destabilization of carbonates in the lower amphibolite facies (Elmer et al. 2006).

In our modeling below, we assume complete destruction of the carbonate assemblage and that all H_2O is lost except that necessary to stabilize the proportion of biotite and muscovite required by the K_2O content of the bulk rock. This assumption is consistent with the general understanding among metamorphic petrologists that upper amphibolite to granulite facies rocks are typically dry (e.g., Spear 1993).

Simulated metamorphism of a gold deposit

It has been recognized for some time that pelitic to quartzofelspathic rocks produce more melt than intermediate to mafic rocks and that rocks that have undergone weathering, or any other hydration process, will produce more melt than anhydrous rocks of otherwise same bulk composition (e.g., Clemens and Vielzeuf 1987; Thompson 1996). However, this concept has not hitherto been applied to partial melting of mineralized rocks. In the following, an orogenic Au deposit from the Victorian goldfields is subjected to simulated metamorphism using the thermodynamic modeling program THERMOCALC (Holland and Powell 1998) to investigate the differences in fraction of melt that would be generated within altered mineralized rock compared to unaltered rock if the deposit was metamorphosed.

The Victorian Goldfields, in southeast Australia, have produced over 2,500 t of Au (Wilde et al. 2004) from numerous small, rich deposits hosted in pelitic to psammitic turbidites spread over a large region. The Wattle Gully deposit (Fig. 1) selected for this study is a typical example (Cox et al. 1995). Globally, the majority of crust-derived felsic magma is generated through melting of sedimentary rocks, similar to the turbidites at Wattle Gully, which contribute to peraluminous granitic magmas (Clemens and Vielzeuf 1987).

Bierlein et al. (1998) have published a detailed account of the alteration at Wattle Gully (including whole rock geochemistry and mineralogical descriptions) and the Victorian Goldfields in general, and the following is summarized from this work. The turbidites at Wattle Gully were subject to lowermost greenschist facies metamorphism, and the gold therein is thought to have been introduced by metamorphic fluids generated during the same tectonic cycle. Unaltered rocks contain metamorphic micas, chlorite, and carbonates. Alteration at Wattle Gully is similar to that found in gold deposits regionally in that the altered rocks are only subtly different to the protolith. The most obvious sign of alteration is the sulfide assemblage of disseminated arsenopyrite and pyrite, with minor sphalerite, galena, chalcopyrite, pyrrhotite, and gold also being observed. These ore minerals are associated with mild carbonate, sericite, and chlorite alteration. The subtle sericite alteration is characterized by low modal abundance of fine-grained K-mica laths developed on cleavage planes and also large blades overgrowing the main structural foliation. Chemical components added to the rock through alteration at Wattle Gully include K, H_2O, CO_2, S, As, and Au. The size of the alteration halo is poorly constrained due to its subtle nature. However, the comparatively easily observable carbonate spotting extends to 30–50 m from the quartz reefs. Arsenic reaches background concentrations at distances as far as 100 m laterally away from the veins. Tourmalinization and albitization is also recognized at some deposits in the region.

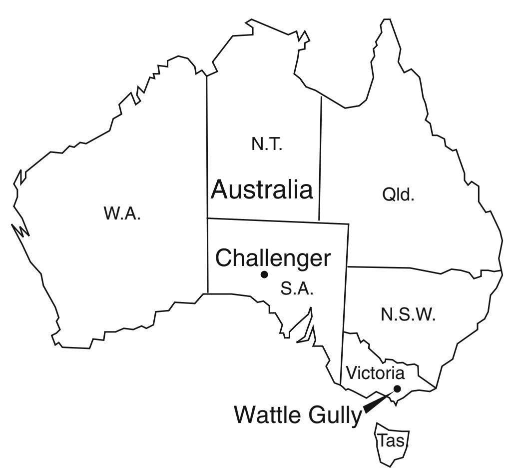

Fig. 1 Location of the Wattle Gully and Challenger gold deposits

Pressure–temperature pseudosections in the system Na_2O–CaO–K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O (NCKFMASH; White et al. 2001) for two bulk compositions (Fig. 2 caption) from Wattle Gully were constructed and contoured for melt fraction (from data published by Bierlein et al. 1998), one for unaltered shale 210 m from ore, and one for altered shale from within the ore zone.

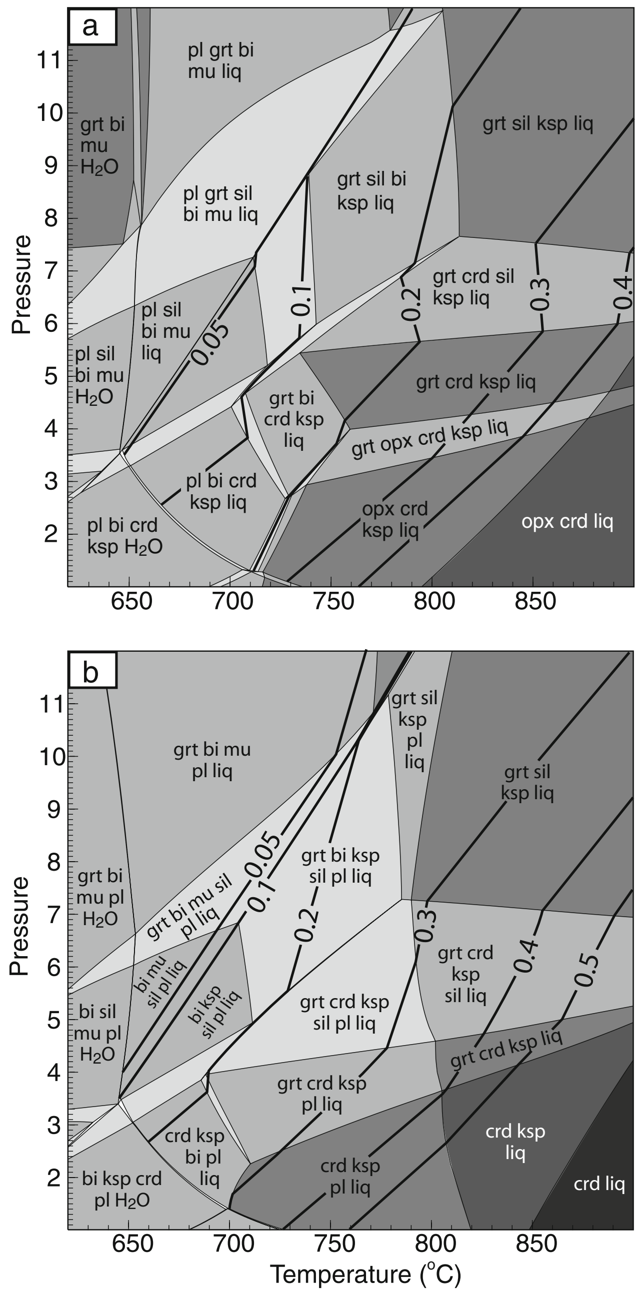

Fig. 2 *P–T* pseudosections calculated in the system NCKFMASH for bulk compositions (data from Bierlein et al. 1998) in the vicinity of the Wattle Gully gold deposit, contoured for melt fraction. **a** Distal unaltered turbidite, bulk composition (mol%): H_2O=4.73, SiO_2= 73.65, Al_2O_3=9.65, CaO=0.08, MgO=3.80, FeO=4.84, K_2O=2.13, Na_2O=1.10. **b** Proximal mineralized, metasomatized turbidite, bulk composition (mol%): H_2O=5.84, SiO_2=72.19, Al_2O_3=10.88, CaO= 0.24, MgO=2.17, FeO=3.26, K_2O=2.46, Na_2O=2.97. H_2O in both cases is the minimum needed to saturate the micas immediately subsolidus at 7.45 kbar

Comparison of these two pseudosections (Fig. 2a and b) illustrates that even mild potassic alteration can significantly influence the melt fraction generated during subsequent metamorphism. They show that under some pressure–temperature conditions, more than double the amount of melt is generated in the metasomatized and mineralized rock.

Variable melting at the Challenger gold deposit: metamorphosed at granulite facies conditions

Pressure–temperature pseudosections were also generated for the Challenger Au deposit (located in the northwest Gawler Craton, South Australia; Fig. 1), which was metamorphosed at granulite facies conditions (~850°C, 7.5 kbar; Tomkins and Mavrogenes 2002). The host rocks at Challenger are a monotonous sequence of graphitic intermediate to felsic metavolcaniclastics with little variation in bulk composition (McFarlane et al. 2007). These rocks underwent variable partial melting over the period 2,443 to 2,428 Ma (McFarlane 2006; Tomkins et al. 2004a, b) to produce a stromatic migmatite with peritectic garnet, cordierite, and orthopyroxene (Tomkins and Mavrogenes 2002). However, some quartz-dominated leucocratic veins within the ore zone are likely to be metamorphosed quartz veins, originally formed during the mineralization event (McFarlane et al. 2007). Ore minerals found at Challenger include gold, löllingite, arsenopyrite, pyrrhotite, native bismuth, chalcopyrite, pentlandite and rare maldonite, sphalerite, molybdenite, and bismuthinite.

Based on the relative abundance of leucosomes and refractory peritectic minerals, observation suggests that unaltered rocks underwent minor partial melting (fewer leucosomes and peritectic minerals; Fig. 3a), whereas mineralized rocks experienced more extensive melting (abundant stromatic leucosomes and peritectic minerals; Fig. 3b). Evidence of melt migration exists within mineralized domains: restitic assemblages that are anomalously rich in peritectic minerals indicate areas of melt loss, and structurally dilatant zones (centimeter to meter in size) filled with quartz, K-feldspar, and plagioclase represent regions of melt accumulation.

Pressure–temperature pseudosections were again constructed in the system NCKFMASH, using bulk compositions (Fig. 4 caption) for the Challenger mineralized gneiss and unmineralized gneiss. Calculated bulk compositions were obtained by correcting whole-rock analyses for melt loss. This correction was done by treating the REE as immobile components during metasomatism and adding a

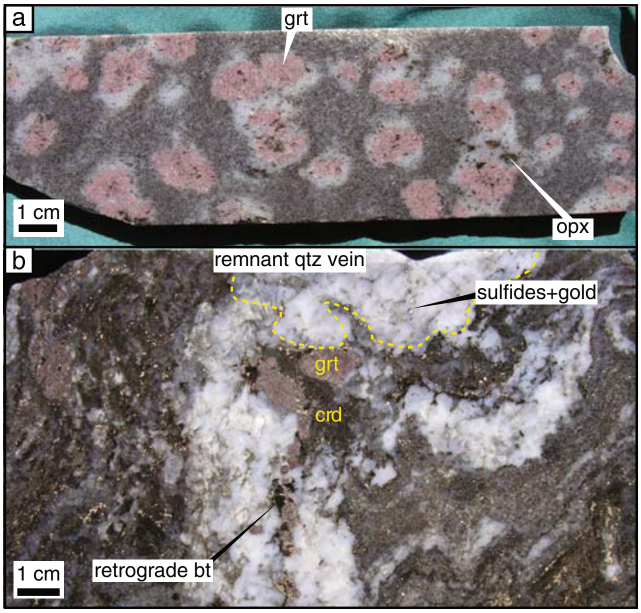

Fig. 3 Unmineralized and mineralized gneisses from Challenger. **a** Leucosome-poor unmineralized garnet-orthopyroxene gneiss. **b** Leucosome-rich gold-bearing garnet–cordierite migmatite. Coarse-grained biotite at garnet margins indicates retrograde reaction between melt and peritectic garnet. Many of the premetamorphic quartz veins at Challenger are partially consumed by locally quartz-undersaturated melts (cumulate quartz-absent, garnet–cordierite–spinel–corundum-bearing assemblages indicate quartz undersaturation), yet retain gold and sulfides within remnant domains such as that pictured. Abundant sulfide grains remain in regions from which melt has been extracted (darker cordierite-rich region to the left), although some are also within the leucosomes

sufficient volume fraction of granitic composition back into the restitic gneiss to reproduce the average REE composition of distal gneisses. Addition of between 30 and 40 vol.% granite was necessary, consistent with other studies (White and Powell 2002) that suggest >30% melt loss is required to preserve anhydrous granulite assemblages. A weakness of this approach is that the latter may also have lost a small degree of melt, which if added would modify the results, making both compositions equally more fertile. The forward modeling on the Wattle Gully deposit was done specifically to accommodate this weakness, to remove any doubt relating to issues of melt loss at Challenger.

An initial set of pseudosections was calculated using the minimum amount of H_2O needed to saturate the minerals immediately subsolidus at 7 kbar. This resulted in significantly different proportions of H_2O in the mineralized gneiss (4.97%) and the unmineralized gneiss (3.40%), reflecting the difference in mica content prior to melting. Under these starting conditions, the activity of water (aH_2O) is 1 prior to melting. However, Challenger contains graphite, and reaction between this and H_2O reduces aH_2O, shifting the initial melting reactions to higher temperatures (Clemens and Vielzeuf 1987). To accommodate this phenomenon a second set of *P*–*T* pseudosections, using the same H_2O contents and bulk compositions, was constructed. This was done using the thermodynamic program PerpleX (Connolly and Cesare 1993) to calculate

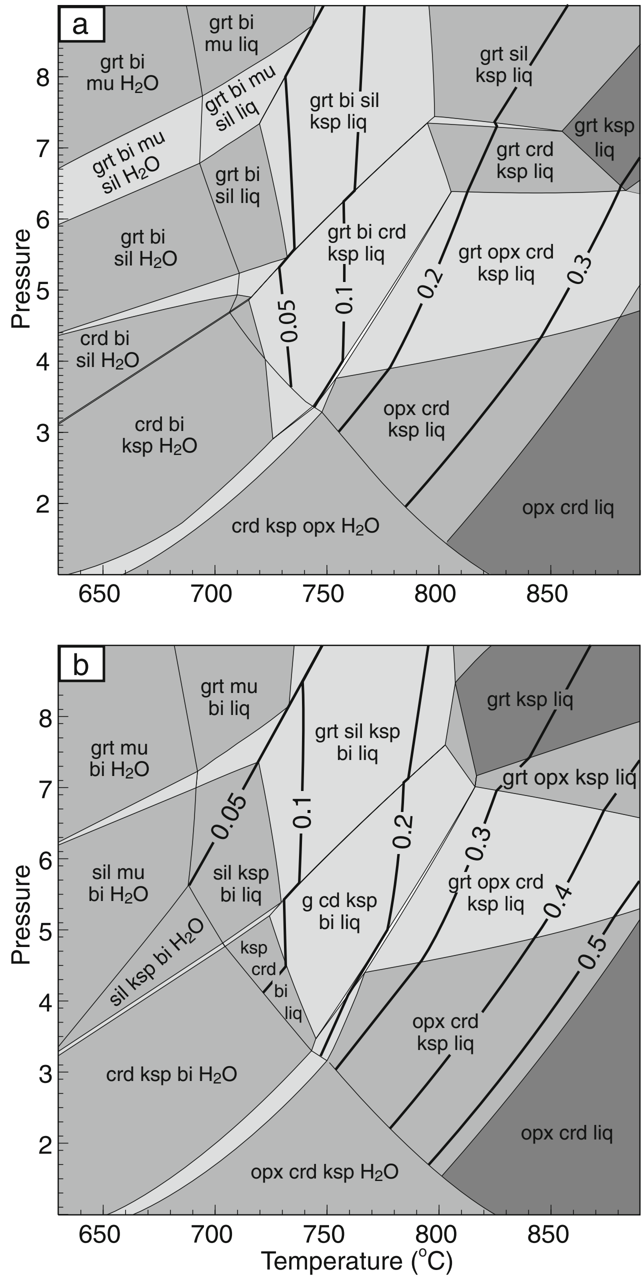

Fig. 4 *P*–*T* pseudosections calculated in the system NCKFMASH for bulk compositions in the vicinity of the Challenger gold deposit, taking into consideration the effect of graphite in lowering aH_2O, on the stability of subsolidus and solidus reactions and contoured for melt fraction. **a** Unaltered gneiss, bulk composition (mol%): H_2O=3.4, SiO_2=71.29, Al_2O3=9.25, CaO=1.89, MgO=3.41, FeO=4.61, K_2O=1.61, Na_2O=2.92. **b** Mineralized, metasomatized gneiss, bulk composition (mol%): H_2O=4.97, SiO_2=69.21, Al_2O_3=10.13, CaO=1.80, MgO=3.91, FeO=4.41, K_2O=2.21, Na_2O=3.36. H_2O in both cases is the minimum needed to saturate the micas immediately subsolidus at 7 kbar

values for maximum XH_2O at the relevant range of temperatures and pressures for a fluid in the presence of graphite. These XH_2O values were then converted to aH_2O and used in conjunction with THERMOCALC to estimate the shift of the sub-solidus and solidus reactions.

The resulting *P–T* pseudosections (Fig. 4a and b) indicate that at moderate pressures, muscovite disappears prior to melting in unmineralized gneiss, but not in mineralized gneiss, and that for a wide range of *P–T* conditions, the melt fraction is more than double that for unmineralized gneiss. The pseudosections, therefore, match the rocks well, with higher melt fraction in the mineralized gneiss and similar peak metamorphic mineral assemblage (orthopyroxene–garnet–cordierite). This difference is related directly to addition of K and H_2O in the mineralized domains prior to metamorphism, which would have produced a more muscovite-rich and, thus, more H_2O-rich, protolith. In the mineralized gneiss, there would have been more melt produced through muscovite melting, together with more sillimanite production during muscovite breakdown. Sillimanite is the limiting reactant in the garnet-producing melting reaction in both gneisses (as evidenced by preservation of quartz, biotite, and plagioclase, and complete removal of sillimanite), so, again there would have been more melting through this reaction in the mineralized gneiss.

There are, however, some limitations inherent in using this technique. Because the system NCKFMASH does not take into consideration the stabilizing effect of Ti in Bt, the Bt-breakdown reactions may, in reality, shift significantly towards higher temperatures (White et al. 2002; Challenger biotite has 2.64–6.41 wt.% TiO_2). Furthermore, the pseudosections represent closed systems and, as such, do not take melt loss into consideration.

K metasomatism of mafic rocks and subsequent metamorphism

Mafic rocks are a major host of large gold deposits and also an important source of felsic magma in the deep crust (Clemens and Vielzeuf 1987), so the effect of K metasomatism on partial melting of these must be considered. THERMOCALC cannot model partial melting of mafic rocks; however, assemblages preserved within metasomatized mafic rocks at a range of localities provide constraints that permit a qualitative comparison.

Mafic rocks that have not been subject to K metasomatism typically contain chlorite+plagioclase±quartz±actinolite at greenschist facies conditions, or hornblende+plagioclase±quartz in the amphibolite facies. In contrast, the central alteration assemblage of orogenic Au deposits in greenschist facies mafic rocks typically contains quartz+pyrite+muscovite+carbonate±biotite±albite±chlorite, with K addition accommodated within muscovite and biotite at the expense of chlorite (e.g., White et al. 2003). Orogenic gold deposits hosted by amphibolite are instead typified by biotite- and quartz-rich alteration assemblages at the expense of hornblende (Ridley et al. 2000).

During metamorphism at granulite facies conditions, dehydration melting of amphibolites typically proceeds through reactions such as hornblende+plagioclase+quartz=clinopyroxene+garnet+melt (e.g., Hartel and Pattison 1996). In this reaction, the amount of H_2O produced via hornblende dehydration limits the melt fraction. At high temperature and moderate pressure or greater, muscovite-bearing rocks undergo dehydration melting through reactions such as muscovite+plagioclase+quartz=sillimanite+K-feldspar+melt. This reaction occurs at lower temperature than the hornblende dehydration reaction (e.g., Spear 1993), so among mafic rocks, melting would occur first in zones of muscovite-bearing hydrothermal alteration associated with gold mineralization. Another melting reaction is possible in biotite-bearing amphibolites: biotite+plagioclase+quartz=orthopyroxene+K-feldspar+melt. It has been found, through experiments on a natural assemblage with biotite+hornblende+clinozoisite+plagioclase+quartz, that biotite undergoes dehydration melting followed by melting involving hornblende (Antignano et al. 2001). However, biotite is likely to eventually become more refractory than hornblende as melting progresses, through its sequestration of Ti, which inhibits its propensity to melt (White et al. 2002). Because biotite and muscovite (~4% H_2O) contain more than double the amount of H_2O in hornblende (~1.5% H_2O), the melt fraction generated by dehydration melting of either is significantly more than that generated by the same proportion of hornblende dehydration. Therefore, high temperature metamorphism of mafic rock-hosted gold mineralization is likely to produce a higher melt fraction, earlier, than the unmineralized equivalent.

Discussion

Effect of melt fraction on melt extraction

Extraction of intergranular melt from partially molten rocks is driven by both buoyancy and deformation, but the latter is critical for efficient melt segregation (Brown 1994). Melt generation and transport are preferentially focused within shear zones because a range of feedback mechanisms localize melting and shearing together (Mancktelow 2002). Rocks with melt are weaker than unmelted rocks and thus localize strain as soon as melting starts (Rosenberg and Handy 2005). Similarly, rocks with greater melt fraction are weaker than melt-poor rocks. Melt fraction is, therefore, the dominant control on the strength of the lower crust (Rosenberg and Handy 2005) and dictates, through strain partitioning, the loci of melt extraction during deformation. Furthermore, pressure gradients within shear zones, whether related to a dilational component, specific dilational sites such as jogs (Brown and Solar 1998) or, more generally, internal fracturing (Mancktelow 2006), attract melt into shear zones. Thus, shear zones control magma transfer through the crust (Brown and Solar 1998).

The ability of K-altered mineralized zones to melt early, and to produce higher melt fractions than their immediate surroundings, implies that they are more likely than their surroundings to localize strain. Furthermore, the greater rate of melt production, coupled with other strain weakening processes, implies that these zones will continually partition strain and attract more magma from the surroundings. As the process develops, incipient magma-rich shear zones will grow and link up with other nearby active and melt-rich shear zones, thereby connecting into a network of magma transfer and stress release. In this way, mineralized zones may become part of a larger-scale transfer system that attracts magmas from the surroundings and feeds them into the network, potentially allowing metal enrichment of the traveling magmas and providing natural pathways for magma extraction from the metal-rich source.

Prior to melting, shear zones serve as channel-ways for hydrothermal fluids, and because K is highly mobile in these fluids, shear zones and their immediate surroundings are in many cases K- and H_2O-enriched compared to distal rocks. Therefore, the interconnected greenschist and amphibolite facies fault systems that form the pathways for mineralizing fluids related to orogenic gold deposits are likely to be relatively K- and H_2O-enriched. Like mineralized rocks, preexisting K-enriched, hydrated shear zones are thus likely to have early and relatively high melt production compared to surrounding rocks and are likely to develop into melt-rich shear systems as metamorphism progresses. These melt-rich shear systems are thus able to connect melt-rich mineralized domains into a network of magma-rich shear zones that act as zones of magma transfer to the upper crust.

It should be noted that these arguments only hold true for dehydration melting. Generation of high melt fractions in zones of K alteration is only effective because K addition allows formation of a higher proportion of hydrous minerals, which in turn allow more melt production through greater H_2O liberation during dehydration. This becomes insignificant when a large amount of externally derived H_2O allows widespread vapor-saturated melting. Vapor-absent conditions are, however, thought to dominate the lower crust (Clemens and Vielzeuf 1987).

Effect of lithological heterogeneity on melt extraction

From the above discussion, it is evident that in an unmineralized heterogeneous package of rocks consisting of pelitic material interspersed with mafic material, which at granulite facies conditions generate high and low melt fractions respectively, the pelitic rocks would be the focus of melt extraction. However, what should be expected from the same package of rocks containing mineralized mafic material: would any melt be extracted from the mineralized domains? Since we cannot model melting in mafic rocks, we cannot answer this question quantitatively. Muscovitic alteration assemblages are observed in extremely altered mafic rocks in gold deposits (at the Golden Mile for example; White et al. 2003), which would generate early melt when metamorphosed, thereby becoming favorable sites for melt extraction. However, low-muscovite, biotitic assemblages are also common in altered mafic rocks, and these must be considered. Our observations, and those of others (e.g., Garrido et al. 2006; Hartel and Pattison 1996), of many lower crustal terrains indicate that melt is extracted from metamorphosed mafic rocks, despite their comparatively low melt fraction. In addition, many granitic rocks are thought to be partly derived from melting of mafic source rocks (e.g., Chappell and White 2001).

Once melting and shearing-induced melt extraction has commenced in early melting lithologies (the pelite in our example), removal of melt creates a pressure differential that is relieved by migration of melt from adjacent melt-bearing domains, provided that a continuous melt network is present. The limited degree of melt network connectivity and high viscosity of felsic melts restricts the length scale of this process, although the dimensions of this are not well constrained in the literature. Thus, in granulite facies terrains, there are many points from which melt can be extracted, so this process allows melt extraction from broad regions that can include relatively low melt domains. At temperatures slightly higher than the initial muscovite dehydration melting reactions, biotite dehydration melting commences, in both pelitic rocks and K-altered mafic rocks. At this point, the K-altered, biotitic mineralized volume within the mafic body in the example above would experience a higher degree of melting than the immediately surrounding unmineralized mafic rocks. It thus would become the locally dominant melt extraction pathway, allowing it to link in with the regional melt extraction network. Similarly, in intermediate to pelitic bulk compositions, potassic alteration causes a higher proportion of melt to be generated through biotite dehydration melting (Figs. 2 and 4). In this way, biotite alteration is also important for promoting preferential magma extraction from K-enriched crust.

Implications of voluminous melting associated with potassic alteration

Metals and sulfur can escape through shear-related pathways with silicate melt, forming metal-enriched batches of magma in three ways. In combination, these three mechanisms cannot only lead to enrichment of gold, but also the range of other elements comprising the ore mineral assemblage, including sulfur. Firstly, sulfide minerals can partially dissolve in felsic melts, which are then locally sulfur-saturated. However, the solubility of sulfides and gold in felsic melts is low (e.g., Frank et al. 2002; Li and Ripley 2005; Liu et al. 2007), so only a trace fraction of the total ore mineral budget in any given metamorphosed deposit can be incorporated in this way. Although recently it has been found that the solubility of gold in reduced felsic melts (sulfide stability field) is directly dependant on fS_2, with higher fS_2 values corresponding to higher gold solubilities (up to 5,200 ppb Au; Jego et al. 2007), indicating that, under appropriate conditions, a significant proportion of Au can escape via this mechanism. Scheelite is highly soluble in felsic melts, with solubilities exceeding 1,000 ppm (Stemprok 1990), so any tungsten present can also be extracted by this mechanism.

Secondly, gold-bearing metal–sulfide–sulfosalt assemblages can partially melt (Tomkins et al. 2004a, b; Tomkins et al. 2007), allowing them to migrate with silicate magma as immiscible sulfide melt blebs during deformation-induced melt migration (Tomkins and Mavrogenes 2002, 2003). In summary, these authors suggested that because sulfide and silicate melts both respond to strain in the same way, by migrating down pressure gradients towards dilational domains, they migrate to the same structural sites. This process facilitates incorporation of sulfide melt within silicate melt that escapes the lower crust. The settling rate of gold-rich sulfide melts, of the same size as those found at the Challenger deposit, was found to be slower than typical ascent rates of felsic magmas (Tomkins and Mavrogenes 2003).

The above two mechanisms are not capable of removing all of the gold present in a deposit because (1) the local concentration of gold in deposits often far exceeds its solubility in felsic magma (e.g., the average grade of Challenger is 8.6 ppm and locally exceeds 2000 ppm), and (2) not all of the gold melts because it is not all in chemical communication with enough of the sulfosalt phases required for 100% melting (e.g., numerous gold deposits contain grains of gold chemically isolated within quartz veins). Instead, additional solid sulfide, oxide, and gold grains may be physically incorporated within, and carried along by, felsic magma. Physical incorporation can occur via entrainment of unmelted masses of sulfide- or oxide-bearing residual rock, particularly in a diatexite migmatite, which then become xenoliths (cf. Clarke 2007). In addition, individual ore mineral grains can be entrained as melt migrates from the site of melting through migmatitic leucosomes and into a granitic accumulation. This physical entrainment has been demonstrated to occur with peritectic garnet (Stevens et al. 2007), which is has been found in many peraluminous granitic intrusions. By using the diameter of naturally occurring garnet xenocrysts in granite (e.g., Jung et al. 2000) and Stokes' Law, it is possible to evaluate the equivalent size of a pyrrhotite or gold grain that can be physically incorporated this way (one assumes that since the garnet is observed in the granite it cannot have settled out). Using a conservative garnet diameter of 5 mm, density for granite of 2,750 kg m^{-3}, and viscosity for granite of 10^5 Pa s (Scaillet et al. 1998), we find that a garnet crystal of this size equates, in settling rate, to a pyrrhotite grain of 4.04 mm diameter or a gold grain of 1.35 mm diameter. Since these diameters are significantly larger than most sulfide or gold grains found in natural deposits, the conclusion is reached that these ore mineral grains can be physically entrained within magma escaping the lower crust.

At this point, it would be fair to ask why the Challenger deposit exists at all if it has undergone migmatization. Challenger consists of a series of three main narrow (~20 m), shallowly plunging ore shoots within a >300 m long As-rich trend that cuts across the dominant structural fabric. These ore shoots are structurally dilatant features relative to the more highly strained inter-ore shoot domains (Tomkins and Mavrogenes 2002). It is believed that the inter-ore shoot domains were part of the original mineralized body prior to peak metamorphism. As melting and deformation progressed, melt and metal may have been preferentially extracted from these inter-ore shoot domains, whereas the adjacent, comparatively dilational domains retained melt and metal or were perhaps even sites of some melt accumulation. This interpretation is consistent with the observation that leucosomes within the ore shoots display textures indicative of retrograde reaction between melt and peritectic phases, indicating melt preservation, as well as the presence of thick leucocratic accumulations. Given the relative volume of the inter-ore shoot domains, more metal may have been lost from the Challenger deposit than retained within it.

The metal and sulfur content of magmas escaping the lower crust depends on which extraction mechanisms are operating, the richness of the source, as well as magma migration dynamics, and thus may be locally highly variable. Mixing with sulfide-undersaturated magmas in shear zones would lead to dissolution of physically incorporated sulfides. Because most of the lower crust is relatively reduced (e.g., Spear 1993), including metamorphosed sulfide deposits (being pyrrhotite-rich at high temperatures), the resulting felsic magmas are reduced and relatively metal-enriched. The magmas do not need to be K_2O saturated—for this to be the case, the melting reactions need to have quartz or plagioclase as the limiting reactants, which is unlikely when the intensity of alteration is mild, as seen in many orogenic gold deposits (in both of the modeled deposits, muscovite is a limiting reactant). The magmas may nevertheless be expected to be relatively potassic, as muscovite is usually the limiting reactant in most source regions. A further constraint is that migmatitic melts derived from partial melting of muscovite-rich quartzofeldspathic or pelitic compositions should be metaluminous to peraluminous.

The relative proportions of magmas sourced from mineralized and unmineralized rock will influence the metal content of a given body of felsic magma. K-enriched mineralized zones are only small, localized occurrences within broader regions that contain significant variability in fertility. Within any broader region undergoing high-grade metamorphism and partial melting, there will be numerous localities of preferential melt extraction, most of which will be unmineralized. However, the enormous volumes of felsic intrusions, and the proportion of melting of the lower crust implied by migmatite textures, require coalescence of magmas sourced from very large regions of lower crust. Potassic alteration-associated voluminous melting and strain partitioning-controlled melt extraction are therefore significant in that these raise the ratio of magma from metal-rich sources to that from low-metal sources. Ideal conditions for generation of metal-enriched crust-derived magmas are a combination of minimal wet melting and low degrees of dehydration melting in regions with a high proportion of zones with mineralized potassic alteration.

Implications of preservation potential for crustal metal recycling

The higher preservation potential of the deeper-formed orogenic gold deposits means that they are more likely than other deposit types to eventually be tectonically emplaced into a position where they can be metamorphosed at high *P*–*T* conditions. Thus, more of the metals found in these deposits, Au, Ag, As, Bi, Te, Sb, and W, can be recycled into the upper crust through partial melting of mineralized crust, than those associated with upper crustal ore deposits (mainly Cu and Mo, but also Au, Ag, Pb, Zn, Hg from epithermal deposits). Metals from the upper crustal deposits are recycled via sedimentary basins, in which metals will be dispersed at background level concentrations. In some cases, metals in this setting can be concentrated again via formation of exhalative type ores, but this process mainly concentrates Pb, Zn, and Ag without formation of potassic alteration halos. When these basins undergo orogenesis, the exhalative deposits are not the focus of melt extraction, and metals are not preferentially extracted from any particular locality. This statement can be assessed by looking at the Broken Hill deposit in Australia, which was metamorphosed at granulite facies conditions. Well away from the mineralized zones at this locality, there has been widespread partial melting of pelitic to psammopelitic assemblages (e.g., White et al. 2004), but there is comparatively little silicate melting within the deposit. The implication of these arguments is that in the main, Cu and Mo need to be added to the crust from the mantle to form new ore deposits, whereas Au, Ag, As, Sb, Bi, Te, and W can be partly sourced from zones of enrichment in the crust.

These arguments allow an assessment of broad regions, which might help to distinguish those favorable for generation of intrusion-related ore systems. In tectonic settings where metamorphism results from heating from below, deep-crustal regions devolatilize early, possibly allowing formation of orogenic Au deposits at mid-crustal levels, which could be metamorphosed as the thermal pulse reaches the mid-crust (Stuwe 1998). However, the magnitude of this late thermal pulse is unlikely to be great enough to cause regional vapor-absent melting at mid-crustal levels. Crust-derived felsic magmas generated in this setting may instead be dominated by melt from metal-depleted lower crust.

For most types of potassic alteration-associated mineralization to undergo partial melting during regional metamorphism, they must go through a second cycle of tectonism. The mineralized protolith is therefore more likely to be relatively old crust due to the time needed for mineralized crust to form in one tectonic event, stabilize, and then become metamorphosed during a second tectonic event. Neoarchean crust, the mid-crustal levels of which generally contain a relatively high proportion of orogenic gold mineralization associated with potassic alteration, would be an ideal basement. The region surrounding the Challenger deposit is an example of such a basement, with numerous occurrences of gold anomalism reported within a broad region of granulite facies metamorphosed Neoarchean crust. In another example, generation of Mesozoic granitic magmas that host gold deposits in the North China craton (Zhou et al. 2002) arguably involved partial melting deeper within the Archean basement that they intrude. However, some younger crustal regions such as the Victorian Goldfields (Ordovician–Devonian), with numerous turbidite-hosted orogenic gold deposits, would be ideal for regional generation of metal-enriched felsic magmas. It may be that crust of this age underlies some of the younger mineral belts with intrusion-related gold systems.

Intrusion-related gold systems have been suggested by others to involve magmas of largely crustal derivation.

These are associated with reduced alkalic to calc-alkalic, metaluminous to peraluminous intrusions (Lang and Baker 2001); compositions that are consistent with derivation, at least in part, from the altered crustal sources under discussion. These authors noted that despite uncertainties between and within provinces, most or all intrusion-related gold deposits formed above or within old, typically cratonic continental crust in a setting well removed, or most distal, from convergent margins active at the time of magmatism. We therefore suggest that preexisting gold mineralization within this old continental crust may be recycled through partial melting to become an important contributor to the metal budget of intrusion-related gold systems. Furthermore, given that mixing between mantle- and crust-derived magmas is possible in continental arcs and some complex island arcs (cf. Richards 2003), melting of old crustal gold mineralization may also contribute to the metal budget of gold-rich porphyry Cu deposits.

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