The orogenic gold deposit model and New Zealand: consistencies and anomalies

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Abstract

Lode gold deposits of the Western and Eastern provinces, South Island, New Zealand, formed as a part of the Cordilleran-style tectonism during Tasman/Tahua and Rangitata orogenesis along the Paleozoic-middle Mesozoic southern Gondwanan margin. These deposits, hosted by lower grade greenschist facies sedimentary rock sequences of the Buller, Takaka, Torlesse, and Caples terranes, universally show geological features that are consistent with the orogenic gold deposit model, and genetic features are generally suggestive of a metamorphic origin, with the possible exception of a magmatic fluid source for the mineralization at Sams Creek. However, ore fluid chemistry in Mesozoic deposits of the Eastern province, particularly the low concentration of non-aqueous volatiles and the very dilute nature of the fluids, is uncharacteristic of most orogenic gold deposits; this must be explained by either a unique fluid source or fluid type, which we believe unlikely, or an unrecognized significance of relatively rare gas-rich fluid inclusions in the deposits. Absolute age data for gold deposits in both provinces remain equivocal, thus hindering definition of the exact temporal relationship between ore formation and terrane accretion, regional metamorphism, and magmatic arc emplacement. Mercury and antimony occurrences in sub-greenschist grade parts of the Haast Schist may target the upper levels of unrecognized orogenic gold deposits. If low-grade, high-tonnage intrusion-related gold systems occur on the South Island, then they are most likely to be discovered in association with the small molybdenite-, scheelite-, or cassiterite-bearing quartz stockworks spatially related to the Karamea and Median batholiths.

Keywords: *orogenic gold, intrusion-related gold, New Zealand, Reefton, Macraes, Otago*

Introduction: Phanerozoic orogenic gold - defining characteristics

Epigenetic gold deposits in metamorphic rocks are inherent products of voluminous fluid flow in Phanerozoic Cordilleran orogens that evolved along the margins of Gondwana, Laurentia, and the more recent circum-Pacific (Goldfarb et al., 2001, 2005). Almost 40,000 t Au have been recovered from these orogens, approximately half from orogenic gold deposits and half from associated alluvial concentrations. Most of these deposits formed during the late stage of orogeny, are located adjacent to deep crustal fault zones that serve as fluid conduits, show a spatial association with greenschist facies rocks, and a spatial and temporal association with widespread calc-alkaline magmatism (Groves et al., 1998; Bierlein & Crowe, 2000). The ores form on retrograde parts of P-T-t paths within an evolving orogen and hence are discordant to most metamorphic features in host terranes (Stüwe, 1998). Mineralization styles vary from ductile to brittle, and include crack-seal veins, stockworks, breccias, and disseminated orebodies. Low sulfide contents (typically 2-5 volume %) dominated by arsenopyrite and pyrite, low base metal concentrations of the ores, a broad range in crustal formation depth (3-20 km), and high $d^{18}O$ (>5 per mil) and CO_2 (10-30 mole %) within the ore-forming fluids are consistent characteristics of this type of gold deposit. Changing mineral economics and improved extraction techniques during the last few decades have resulted in the development of lower-grade orebodies (perhaps down to 1 g/t Au) adjacent to high grade zones (often e”5-10 g/t Au) in orogenic gold deposits that were commonly mined out as much as one century earlier.

There have been numerous ore genesis models proposed for the orogenic gold deposits during the past 25 years, but an overall consensus is still lacking (e.g., see review in Goldfarb et al., 2005). The syngenetic seafloor and meteoric water hypotheses are no longer widely accepted; a minority of workers still support magmatic or mantle fluid/metal source models. Nonetheless, the majority of workers accept some type of metamorphic model, with fluids and metals being derived from the accreted host terranes and/or from subducted oceanic material. Many of the concepts for such a metamorphic model for gold ore formation were developed by researchers studying the major gold ores of the South Island of New Zealand (Grindley & Wodzicki, 1960; Williams, 1974; Henley et al., 1976; Paterson, 1986; Craw, 1987, 1992; Craw & Norris, 1991)

South Island, New Zealand: Displaced fragments of a Cordilleran-type margin

The South Island of New Zealand is now well recognized as a collage of allochthonous terranes representing both far traveled and more localized rifted fragments of the Paleozoic-middle Mesozoic Gondwanan accretionary orogen (e.g., the progressive Ross-Delamerian, Tasman/Tahua, and New England/Rangitata events). In fact, some of the initial concepts regarding terrane theory and migration recognized the “suspect” affinity of many lithostratigraphic sequences in New Zealand (i.e., Blake et al., 1974; Bradshaw et al., 1981). Such sequences of dominantly clastic metasedimentary rocks, in both the Western and Eastern provinces, are no different than similar Cordilleran-like terranes of other active continental margins, which are characterized by voluminous syndeformational fluid flow and the widespread distribution of orogenic lode gold deposits in structurally favorable environments (e.g., southeastern Alaska, western Lachlan fold belt, eastern Russia). Also, like most Pacific Rim orogenic gold provinces, much of the gold endowment has been reconcentrated in productive placer fields.

One exceptional feature, however, leading to additional complications regarding the understanding of the South Island scenario, is the post-collisional rifting along the supercontinent margin, which is reflected in the ca. 85 Ma (Luyendyk, 1995) opening of the Tasman Sea. This is the sole example where significant orogenic gold deposits formed along the Mesozoic-Cenozoic Pacific Rim have been subsequently rifted from their continental margin position. In fact, there are no other well-recognized global examples where a Phanerozoic orogenic gold deposit has moved far seaward from its original continental margin.

The Western province is dominated by Late Cambrian-Early Ordovician turbidites (i.e., Greenland Group) of the Buller terrane and Cambrian-Devonian assemblages of the Takaka terrane. The terranes were sutured in the Middle to Late Devonian (Cooper, 1989), with the Buller terrane likely being an extension to the western Lachlan Fold Belt (Cooper & Tulloch, 1992) or eastern Lachlan Fold Belt (Adams et al., 2005), and the Takaka terrane to western Tasmania (Cooper & Tulloch, 1992) or northern Victoria Land (Cooper, 1989). Collision-related regional deformation, high T-low P metamorphism, and intrusion of the dominantly S-type bodies of the Karamea batholith define the ca 380-365 Ma Tuhua orogen (i.e., Muir et al., 1996; Ireland & Gibson, 1998; Wandres & Bradshaw, 2005) along the southern Gondwanan margin. Gold deposits and igneous rocks of middle Paleozoic age characterize the 20,000-km-long accretionary margin of the Gondwanan continent (Muir et al., 1996; Goldfarb et al., 2001), which include those of the Western Province.

The Eastern province of New Zealand is defined by a series of Permian to Cretaceous turbidite and arc terranes that were progressively amalgamated with the Western province between ca. 245 and 140 to 120 Ma (Adams et al., 1998; Mortimer et al., 1999; Gray & Foster, 2004). The final two terranes that were added to the continental margin sometime during Late Jurassic-Early Cretaceous, the Caples terrane and Torlesse superterrane (i.e., amalgamated Rakaia and Pahau terranes), host orogenic gold deposits in a region of widespread medium-grade regional metamorphism defined by the Haast Schist. The peak of this metamorphism may have been as old as 180-170 Ma (Mortimer, 1993; Little et al., 1999) or as young as 150-140 Ma (Gray & Foster, 2004), and likely relates to subduction of the Torlesse superterrane below the Caples terrane (Wandres & Bradshaw, 2005). It is also likely that such metamorphism approximates the time of accretion of these two terranes to the Gondwanan margin. Rapid cooling and exhumation of the metamorphosed rocks likely occurred from 140-130 Ma (Little et al., 1999), although Gray and Foster (2004) suggest this may have occurred 30 m.y. later.

The Carboniferous to Early Cretaceous Median batholith, located between the two provinces, is now widely accepted to represent a classic Cordilleran-type, calc-alkaline, subduction-related continental magmatic arc (Mortimer et al., 1999). The igneous bodies intrude rocks of the Western Province and also mark the suture between terranes of the two provinces; the intrusions temporally overlap the deformation, metamorphism, and gold-forming events in the Eastern Province fore-arc. Such a relationship is similar to events in other Cordilleran-type margins, such as those that define the Mother Lode belt seaward of the Sierra Nevada in California and the gold provinces seaward of the Tertiary Alaskan coastal batholiths (e.g., Goldfarb et al., 1998). However, in contrast to these other auriferous regions, the fore-arc to the Median batholith lacks additional igneous activity.

Paleozoic gold of the Western province

The characteristics of the gold deposits in the Western province, such as those at Golden Blocks, Lyell, Reefton, Langdons, Mt. Greenland, and Preservation Inlet, are consistent with the orogenic gold model. The most productive lode deposits occur in the Reefton district, hosted in greywacke and argillite that are folded and metamorphosed to lower greenschist facies (Barry, 1993; Christie & Brathwaite, 2003). Mineralized veins, breecia, and disseminated ores occur along relatively NNE-striking shear zones and reverse faults that follow axial planes of regional folds (Henderson, 1917; Gage, 1948; Rattenbury & Stewart, 2000; Christie et al., 2001; Bierlein et al., 2004). Ore mineralogy, alteration assemblages, and isotope and fluid inclusion geochemistry are consistent with other orogenic gold deposit systems (Christie et al., 1999, 2001, in prep.; Christie & Brathwaite, 2003; Bierlein et al., 2004). The Reefton deposits are located about 10 km west of the Karamea batholith. The distribution of productive placers throughout the Buller terrane also suggest localization of most source lodes within the greenschist facies rocks and not in the higher grade areas.

The timing of ore formation in the Western province remains uncertain. In the Reefton district, the lack of auriferous veins or alteration within rocks of the middle Early Devonian Reefton Group or younger strata led Brathwaite and Pirajno (1993) to suggest a relative age of ore formation >390 Ma. This is consistent with a variety of poorly constrained K-Ar (Hunt and Roddick, 1993) and Ar-Ar (Christie et al., in prep.) data for hydrothermal mica, which show numerous equivocal dates as old as ca 500 Ma (detrital?) to 386±8 Ma. The lower end to this range overlaps Tuhua orogenesis (ca. 380-365 Ma) and would be consistent with what is observed for most orogenic gold provinces. Such an age would significantly post-date the ca. 455-435 Ma deformation, metamorphism, and the major gold forming events of the perhaps adjacent western Lachlan fold belt (i.e., Bierlein et al., 2001), although it would be coeval with later phases of magmatism and gold mineralization in the eastern and central parts of the Victorian goldfields region. The younging of goldfields in a seaward direction in a growing orogen (i.e., Alaska, Chinese Altaids) is typical of Codilleran-style collisional orogenesis and is not unexpected if indeed the Western Province goldfields developed on the edge of the Lachlan fold belt (i.e., Goldfarb et al., 1995). Typically orogenic gold provinces develop in the fore-arc region of an active margin and thus the westerly location of the Western province gold deposits relative to the potentially coeval Karamea batholith system is unusual unless the Buller terrane was rotated 180^{o} from its Paleozoic position along the Gondwanan margin.

Mesozoic gold of the Eastern province

There are both consistencies with, as well as major contrasts between, lode gold deposits hosted by rocks of the Haast Schist and orogenic gold deposits as a whole. The most significant lode system, Macraes, is associated with the 25-km-long Hyde-Macraes Shear Zone, with brittle to ductile orebodies concentrated along dilational jogs and local extensional zones (Teagle et al., 1990) during fault reactivation (Windsor, 1991). Gold lodes and associated placers show a spatial association with areas of Haast Schist, which is suggestive of an association between ore formation and metamorphic processes, as first detailed in the now classic model of Henley et al. (1976). Pitcairn et al. (2003) have recently documented the mobilization of metals that are commonly present within the gold lodes from the more thermally upgraded parts of the Otago part of the Haast Schist. Vein formation temperatures and pressures, gold vein mineralogy, and istopically heavy oxygen isotope data for ore-related quartz (Paterson, 1986; McKeag & Craw, 1989; Craw, 1992) are all consistent with orogenic gold deposits worldwide. Similar to many other orogenic gold deposits, the sulfur in the ores that almost certainly carries the gold is derived from rocks of the host terranes (Craw et al., 1995)

The ore-forming fluid chemistry at Macraes and at a number of smaller auriferous lodes within the schist in the Caples and Torlesse terranes is, however, exceptionally anomalous. Reported data from microthermometric study are >99% H_2O and typically only 1-2 wt. % NaCl equiv. (McKeag & Craw, 1989; Craw, 1992). Mass spectrometry work by de Ronde et al. (2000) identified CO_2, CH_4, and N_2 within the ore-forming fluids at Macraes, but these data also reemphasized that the fluid itself was overall >99% H_2O. They compared the Macraes fluids to those in some geothermal systems in the Taupo Volcanic Zone, such as Broadlands-Ohaaki. We know of no other important province of orogenic gold deposits where the most widespread recognized ore-related fluid is so poor in carbon-bearing volatile species.

There are a variety of possibilities to explain the reported dominance of these very dilute, essentially aqueous ore-forming fluids. One possibility is a unique fluid source for gold transport throughout much of the Haast Schist. This could include a relatively greater role of meteoric or magmatic (e.g., de Ronde et al., 2000) water than in most orogenic gold systems. However, we would suggest such argument lacks strong supporting evidence due to the unreliability of hydrogen isotopes from fluid inclusions for fingerprinting surface fluids (e.g., Pickthorn et al., 1987) and to the lack of outcrop of major intrusions within ~180 km of Macraes and tens of kilometers to any gold-bearing parts of the Haast Schist. A second scenario could be a very limited amount of C-bearing material within sedimentary rocks during the prograding of the appropriate parts of the Torlesse and Caples terranes. However, this too seems unlikely, as CO_2-rich fluids are recognized during medium-grade metamorphism of essentially all turbidite and volcaniclastic terranes, and there seems to be nothing different about these very typical lithostratigraphies. A third, more straightforward, and herein preferred option, is that CO_2 and (or) CH_4 may have been more abundant in the auriferous hydrothermal systems than has been previously acknowledged. Typical carbonate alteration, although with calcite being more common than ankerite at higher temperatures (Craw et al., 1991), supports such a presence of significant CO_2 in the hydrothermal systems. In fact, Craw (1987) did identify significant CO_2 during microthermometric study at Macraes, but interpreted the species as post-gold. McKeag and

Craw (1989) mentioned CO_2-bearing fluid inclusions and their decrepitation prior to homogenization in post-gold, scheelite-quartz-carbonate veins at Macraes. Finally, de Ronde et al. (2000) mention "rare" fluid inclusions in the Macraes ore-bearing veins with 4 weight % NaCl equiv. and definite clathrate formation during cooling experiments. These consistent observations of the CO_2 in the Macraes system suggest to us that such a fluid component, perhaps lost from many inclusions during post-entrapment modification or viewed in inclusions that are rare because of an abundance of later secondary fluid inclusion entrapment, could be of more importance than previously noted.

The absolute age of most gold vein formation in the Eastern province remains unclear. Because they are younger than the broadly dated Haast Schist metamorphism, veins can be no older than 180-140 Ma. Potassium-Ar and Rb-Sr age determinations from Barewood, Nenthorn, Oturehua, Bendigo, and Glenorchy suggest gold formation occurred in the Early Cretaceous (ca. 145-100 Ma), after regional metamorphism, and thus during uplift and cooling of the schist (Adams & Graham, 1997, 2000). Similarly, K-Ar and Rb-Sr ages for the Terawhiti veins in schist of the Torlesse terrane near Wellington, mostly cluster between 137-125 Ma (Adams & Graham, 1993). The Macraes Flat mineralisation has been broadly constrained by K-Ar measurements on "micaceous selvedges", as well as by whole rock K-Ar and Rb-Sr dating, as between 158 and 132 Ma (Adams & Graham, 1997, 2000); the same broad Jurassic-Cretaceous age range characterizes K-Ar mica dates from many of the gold deposits hosted by rocks of the Marlborough Schist (Adams et al., 1999). Angus et al. (1997) state that the orebodies at the Macraes deposit range in age over 10 m.y., straddling the Jurassic-Cretaceous boundary (142 Ma). If correct, the 10-m.y.-long duration of the hydrothermal systems at Macraes is relatively long for an orogenic gold system when compared to that of many other gold provinces (e.g., Miller et al., 1994). Also, this ca. 142 Ma timing at Macraes slightly pre-dates most estimates (see above) for final Torlesse terrane accretion to Gondwana and for subsequent rapid uplift of the metamorphic rocks. Such a relative timing contrasts with most global examples, and additional dating would seem needed to verify such an unusual relationship.

As with many accreted terranes along active margins, low metamorphic grade parts of the Torlesse and Caples terranes may be favorable for shallowly-formed mercury- and antimony-rich occurrences. A few small mercury-rich lodes and widespread cinnabar occurrences in placers are in areas mainly near the southern margin of the Otago Schist (Williams, 1974). Stibnite is present in the quartz lodes at Carrick, Macetown, Hindon, Nenthorn, and Waipori in Otago, and at Endeavour Inlet in Marlborough (Williams, 1974). The massive stibnite ore at Endeavour Inlet grades downward to veinlets with, and disseminations of, fine pyrite and arsenopyrite needles, a few hundred meters below the mined antimony ore (Pirajno, 1979). These deeper sulfide-rich zones are also notably anomalous in gold. This is a very similar scenario to that of southwestern Alaska, a Hg-Sb province where a historic stibnite prospect in relatively unmetamorphosed rocks of the North American Cordillera has proven to be the top to a 24 Moz epizonal orogenic gold deposit at Donlin Creek (Goldfarb et al., 2004). Hence, such epizonal occurrences in the Torlesse and Caples terranes could, in some cases, prove to be exploration targets for underlying gold ore systems.

Intrusion-related gold systems in New Zealand?

Some workers (see below discussion) have suggested a possible link between intrusions and the important gold ores within metasedimentary rock sequences on the South Island. We consider that there are no convincing data suggesting deposits such as Macraes or those of the Reefton area should be classified with the intrusion-related group of gold systems. By "intrusion-related gold systems", we mean deposits such as Fort Knox (Alaska) and those in adjacent Yukon that are characterized by low grade (<1 g/t), large tonnage orebodies, typically occurring as sheeted vein networks in the cupolas of their generative plutons (e.g., Hart et al., 2002). Modern mining methods and the high price of gold have made such magmatic hydrothermal systems new economic targets (and thus a new and distinct gold deposit type) during the last 10-15 years

(Thompson et al., 1999; Lang et al., 2000; Hart & Goldfarb, 2005). Furthermore, supporting data for a substantial magmatic input to the formation of the South Island orogenic gold deposits is lacking and the metamorphic model of Henley et al. (1976) still appears most applicable to deposits in both the Eastern and Western provinces.

In contrast to the more typically applied metamorphic model for Macraes and other deposits of the Haast Schist (e.g., Henley et al., 1976; Craw & Norris, 1991), de Ronde et al. (2000) suggested an important fluid component to the deposit was released from crystallising magmas cogenetic with those along the easternmost boundary of the Median Batholith located about 180 km west of Macraes. The most supportive evidence mentioned by de Ronde et al. for such is the apparently coeval ages of gold and magmatism, as well as the unique Broadlands-Ohaaki-like fluid chemistry, discussed above, which is unlike fluids that are reported from other orogenic gold deposits suggested to be of a metamorphic origin. But the required long horizontal flow path between the batholith and the deeply-formed, structurally-controlled Macraes orebody is atypical of crustal hydrology in accretionary terranes. Eastern parts to the batholith could, alternatively, theoretically continue below the Otago Schist (de Ronde et al., 2000), but there is no evidence for such and this scenario is also inconsistent with the subduction-related origin to the plutonic mass.

Similarly, Leach et al. (1997) have discussed a magmatic source for the gold mineralization at Reefton and state the geology is very similar to many intrusion-related gold systems of the Southwest Pacific. They stress a spatial association of gold with lamprophyres (Henderson, 1917) as supportive of a magmatic connection, but as described by Wyman and Kerrich (1989) and Kerrich and Wyman (1994), such an association is generally solely structural, rather than genetic. Whereas the time of Karamea batholith emplacement likely overlaps Buller terrane gold deposition, again there is little evidence supporting magmatic fluid exsolution as being important in the ore-forming process.

The Sams Creek deposit has been classified as both a "slate belt" [orogenic] gold deposit (Windle & Craw, 1991) and a magmatic-related gold deposit, specifically a hybrid between a reduced Au-Bi deposit type and an alkaline intrusive rock-hosted Au-Mo-Cu deposit (Brathwaite & Faure, 2004; Faure & Brathwaite, in press). Gold- and sulfide-bearing quartz±siderite veins and stockworks are structurally hosted by a peralkaline and adjacent lamprophyre dikes that cut metasedimentary rocks of the Takaka terrane. Brathwaite and Faure (2004) note that similarities to orogenic gold deposits are the low sulfidation state of the ore mineral assemblage (arsenopyrite and pyrite), carbonate alteration, and carbonic fluid inclusions. However, they suggest that differences from orogenic gold deposits are stockwork veining, magnetite-siderite±biotite alteration, a high sulfide volume (with the presence of galena, sphalerite, and chalcopyrite, but an absence of scheelite and stibnite), and the restriction of mineralization to the igneous rocks. Also, the $^{187}Os/^{188}Os$ isotopic ratios of arsenopyrite (0.25) suggests a mantle contribution for Os to the ore-forming fluids (modern mantle is about 0.13), rather than a crustal source (>0.4) for the metals (Faure et al., 2005). The exact significance of such is equivocal; in fact, among ourselves, one of us (AC) finds such data convincing, whereas the other two of us would argue the stated differences are not definitive of a magmatic fluid source and the Os could have been locally contributed from the dike, so that the Sams Creek veinlets may indeed be, as stated originally by Windle and Craw (1991), no different than other orogenic gold deposits.

We consider that there is potential in New Zealand for economic intrusion-related gold systems, but that these are likely to be identified in close spatial association with plutons of the Karamea and/or Median batholiths. Gold, molybdenite, scheelite, cassiterite, fluorite, and/or silver occurrences, such as those at McConnochie Creek, Bateman Creek, and Kirwans Hill (Pirajno & Bentley, 1985: Brathwaite & Pirjano, 1993), and in the Paparoa Range-Buller Gorge area, are feasible targets for evaluation as such a gold deposit type of either Paleozoic or Cretaceous age. It may be important to note that the one universally agreed upon example of this deposit type that is presently being mined (i.e., Fort Knox, Alaska) was known as an uneconomic gold prospect for almost one hundred years and it was not until the previous decade that such a low-grade (<1 g/t), sheeted vein system was recognized for its large (>5 Moz Au) tonnage.

Conclusions

The orogenic gold deposit model remains the most applicable to explaining all features of gold ores in both provinces of the South Island. The spatial association of mined gold lodes and lower greenschist facies rocks is consistent with the metamorphic model of ore formation; mercury- or antimony-rich lodes extending into lower grade metamorphic terranes of the Eastern province may target new, less well-exposed orogenic gold systems. More reliable absolute age information on all South Island gold deposits is critical before ore formation can be specifically related to processes of orogenesis along the Gondwanan margin. In addition to orogenic gold formation in metamorphic belts, the potential for intrusion-related gold deposits exists within the upper levels of plutons of the Karamea and Median batholiths.

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