Distinguishing intrusion-related from orogenic gold systems

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Abstract

Reduced intrusion-related gold deposits have become a new, low-grade, large-tonnage exploration target during the last decade. The best recognized examples of such deposits are recognized throughout the Tintina Gold Province of the northern North American Cordillera. Because such examples may have many features in common with orogenic gold deposits, such as anomalous Bi, W, and Te, low salinity and CO_2-rich ore fluids, and a spatial/temporal association with igneous rocks, confusion and controversy have now become commonplace in classification of many gold deposits formed along convergent margins. The best discriminators of IRGS are likely to be their: (1) regional location in deformed shelf sequences on the inboard side of a series of accreted terranes and within terranes that also contain important tin and(or) tungsten deposits; (2) local spatial association of gold ores with cupolas and contact aureoles of relatively-reduced, alkaline-leaning, and volatile-rich plutons; (3) post-deformational timing of gold deposition; (4) extremely low sulfide content (commonly <1 vol. %) of ores within igneous bodies and the outward zoning, through proximal skarns and to distal base metal-rich veins, from the causative pluton; and (5) low grades (<1 g/t Au) of auriferous sheeted vein systems in pluton cupolas.

Keywords: *intrusion-related, gold, orogenic, Yukon, Alaska, ore deposit models*

Introduction

Since the commencement of the modern era in gold exploration and research in 1980, there have been major advances in the understanding and classification of a wide range of gold deposit types. Historically, most gold deposit types were classified according to their depth and temperature of formation (epithermal, mesothermal, and hypothermal), structural style (shear zone type), age (Precambrian gold), host rock-type (greenstone gold, turbidite-hosted gold, slate belt gold), or geographic area (Mother Lode type). In more recent times, with advances in analytical capabilities, there was an increased emphasis on associations with genetic models or fluid sources, thus labeling a deposit as a metamorphogenic, meteoric, evolved meteoric, or magmatic type of gold deposit. Most of these genetic deliberations focused on deposit types now most commonly described as orogenic gold deposits. This terminology came about with increased emergence in the understanding of plate tectonics, crustal evolution, and the nature of crustal-scale fluid flow. Orogenic gold deposits, as defined by Groves et al. (1998), are predominant and broadly synchronous with deformation, metamorphism, and magmatism in the fore-arc region of convergent orogens.

Despite the fact that genetic connections between gold ores and granitic rocks have been long recognized (e.g., Agricola, 1556; DeLaunay, 1900; Lindgren, 1913; Spurr, 1923; Niggli, 1929; Emmons, 1926, 1933), the contemporary geological literature was essentially devoid of intrusion-related gold models. For example, there is no mention of such in milestone contributions that include the 75th Anniversary Volume of Economic Geology (Skinner, 1981) or the U. S. Geological Survey's Ore Deposit Models (Cox & Singer, 1986). Recently, however, intrusion-related models have been emphasized by many workers (e.g., Sillitoe, 1991; Sillitoe & Thompson, 1998; Lang et al., 2000).

Sillitoe (1991) defined a "broad spectrum of gold mineralization styles" within epizonal to mesozonal environments that showed clear evidence of being intrusion-related, using examples mainly from the circum-Pacific arc settings. Sillitoe and Thompson (1998) added to this model by emphasizing the association of several gold-only vein deposits with probable magmatic-plutonic origins. The model further evolved with the contribution of Thompson et al. (1999) that focused upon a wide-range of gold mineralization styles that were genetically associated with intrusions that lacked proximal base-metal occurrences, but had some degree of W and (or) Sn mineralization and a low primary oxidation state (thus differentiating these deposits from porphyry copper deposits and many of the examples described by Sillitoe, 1991). This was coined the intrusion-related gold systems (IRGS) model by Lang et al. (2000), and then modified slightly and termed the reduced IRGS model by Thompson and Newberry (2000) to better emphasize the importance of the reduced state of the associated granitoids.

The reduced IRGS model was mainly developed in response to observations, exploration, and discoveries, and then the subsequent research, on gold systems across central Alaska and Yukon (e.g., Newberry, 1995; McCoy et al., 1997), which collectively comprise the Tintina Gold Province (Hart et al., 2002). Fort Knox in Alaska (Bakke 1995), and Dublin Gulch (Maloof et al., 2001), Clear Creek (Marsh et al., 2003), and Scheelite Dome in Yukon (Mair 2004), are the best described examples of these systems. This relatively recently developed intrusion-related gold deposit model is an extremely appealing concept and has been broadly adopted. It is the topic of special volumes (Tucker & Smith, 2000; Lang & Baker, 2001) and intrusion-related models have subsequently been called upon to describe the genesis of an increasing number of gold deposits and districts throughout the world, including many orebodies that had been previously classified as orogenic gold and/or as metamorphic in origin.

The unrestrained proliferation of this model has led to a great deal of confusion among many economic geologists because critical empirical geological differences between an orogenic gold deposit and an IRGS are often ignored, with an increased focus directed towards genetic features (e.g., Walshe et al., 2005). Beyond the debates and genetic controversies that take place in the geological literature, the main reason for distinguishing between intrusion-related and orogenic gold classifications is the fundamentally different approaches to gold exploration methodology required by each model.

Characteristics of reduced IRGS

Below, we list some of the significant characteristics of IRGS deposits as have been identified in the Tintina Gold Province (TGP) of Alaska and Yukon, which are, the best studied and best known examples of this deposit type.

Global perspective

The intrusion-related gold-bearing deposits, which form the IRGS of the TGP, are found in the well-preserved, moderate- to high-temperature Mesozoic collisional belts of the northern part of the North American Cordilleran orogen. This orogen is typical of many others along the circum-Pacific region, which could include large areas of Mesozoic tectonism throughout the Russian Far East, the margins of the North China craton, and the Eastern province/Median batholith of the South Island, New Zealand. Accretionary orogens of Paleozoic age would include the southern and northern Gondwana margins (Tasman orogenic system, northern Africa, Telfer district, eastern Cordillera of South America), and the northern (Caledonian Kazakhstania, Uralian orogen, Baikal orogen, Tian Shan orogenic system) and western margins (southern European massifs) to the Paleo-Tethys Ocean. Gold lodes in all Phanerozoic metamorphic belts are dominated by orogenic gold deposits, whereas other epigenetic deposit types (porphyry, skarn, epithermal) are concentrated where relatively unmetamorphosed, shallow levels to the orogens are preserved. Importantly, some of the plutonic belts in these Paleozoic-Mesozoic accretionary sequences are likely to be similar to those in the northern Cordillera of North America and thus might be favorable targets for similar IRGS.

Tectonic setting

Reduced IRGS deposits are best developed in intrusions that were emplaced into the region behind an accretionary orogen and into rocks of the deformed continental margin backstop. The TGP deposits occur within Paleoproterozoic and Paleozoic basinal miogeoclinal sedimentary rocks, some of which are carbonaceous and their melting may have assisted in maintaining a low magmatic redox state. Many of the granites intrude unmetamorphosed to low grade sedimentary rocks, whereas others intrude amphibolite facies metasedimentary rocks that were metamorphosed in response to crustal thickening during collision. Although the setting has been called far back-arc (e.g. Thompson et al., 1999), the gold deposit-associated magmatism is not related to typical arc magmatism, and may be several hundred to one thousand kilometers inland from the arc, and younger than plutonism of the arc. There are no volcanic rocks associated with the post-arc intrusions. All gold-related intrusions in the TGP are undeformed, as they were intruded about 10 million years after deformation.

Depth of formation

The intrusions and associated IRGS mineralization exhibit a wide range of characteristics that indicate a range of magmatic and related hydrothermal events at depths of <1km to >8km, with most between 4 and 6 km. Clearly some magmatic-hydrothermal systems were active shallowly, as they are dominated by sills or dykes, and typically host low temperature metal assemblages and alteration phases traditionally thought of as being characteristic of epithermal precious metal deposits, such as an As-Sb-Hg signature. Other auriferous systems include sheeted auriferous veins and W- and Au-bearing reduced skarns in the cupolas and in wide thermal aureoles to plutons. Mineral equilibrium assemblages and fluid inclusion data indicate formation pressures that vary greatly between 0.3 to 3.5 kbar (e.g. Baker and Lang, 2001; Mair, 2004), confirming a variety of depths to pluton crystallisation..

Magmatic setting and association

Several hundred granitoid plutons, dykes, and sills form a series of several hundred kilometer-long, coincident mineral and plutonic belts in the TGP (Mortensen et al., 2000). Among the most prolific, is the Tombstone Belt, which is the youngest and most landward of all the Cretaceous magmatic systems within the orogen (Hart et al., 2004a, b). Most plutons are typically small ($<5km^2$) and are dominated by leucocratic and felsic magmatic phases. There are no batholiths. The magmas are silica-rich (64-72%), and importantly alkalic-leaning, forming quartz monzogranites, monzonites, and locally more mafic (monzodiorite) and more alkalic (quartz syenite) phases. Plutons have many phases, but variations are subtle. Biotite is the dominant mafic mineral, with considerably lesser hornblende, and pyroxene is locally common. The plutons are dominantly metaluminous, but highly fractionated peraluminous phases contain muscovite, garnet, and toumaline. Associated dykes of aplite and pegmatite, as well as numerous mafic phases including lamprophyres, are common. The plutons defy characterization, are not typically calc-alkaline, are locally alkalic, and geochemically plot in the I-type field, but mostly lack hornblende and magnetite. Most plutons are considered ilmenite series because they lack magnetite. Initial Sr isotope values in excess of 0.71, epsilon Nd values between –8 and –20, and $d^{18}O$ values of 12-15 per mil, attest to a large crustal contribution to the magmas (Marsh et al., 2003; Mair, 2004).

Deposit variation and zonation

There is considerable breadth in the metallogeny of the mid–Cretaceous plutons of the TGP (Fig. 1). Igneous bodies host associated tungsten, molybdenum, silver, uranium, tin, copper, and gemstone concentrations, in addition to the gold. Additionally, there is considerable, but predictable variation in the styles of mineralization and the elemental associations of gold occurrences surrounding any individual pluton. These include **intrusion-hosted** sheeted and rarely stockwork auriferous quartz veins (Au±Bi±W±Te). The intrusion-hosted ore assemblage contains high fineness gold intergrown with bismuth- and tellurium-bearing phases, which locally are associated with scheelite. Skarns are present in **contact** zones adjacent to the intrusions (Au±W, Cu±Bi±Te); **proximal,** thermal aureole-hosted replacement, disseminated, and fracture controlled mineralization occurs in metasedimentary rocks (Au-As±Sb); and fissure **veins** vary outward from Au-As to Au-As-Sb to Pb-Zn-Ag (Thompson et al., 1999; Lang et al., 2000; Hart et al., 2000, 2002). The deposits typically show an evolution from early, high-temperature magmatic stages to lower temperature hydrothermal veins. The spatial relationships and metal assemblages of the occurrences are zoned with respect to a central mineralizing pluton in response to steep temperature and fluid chemical gradients away from the causative pluton.

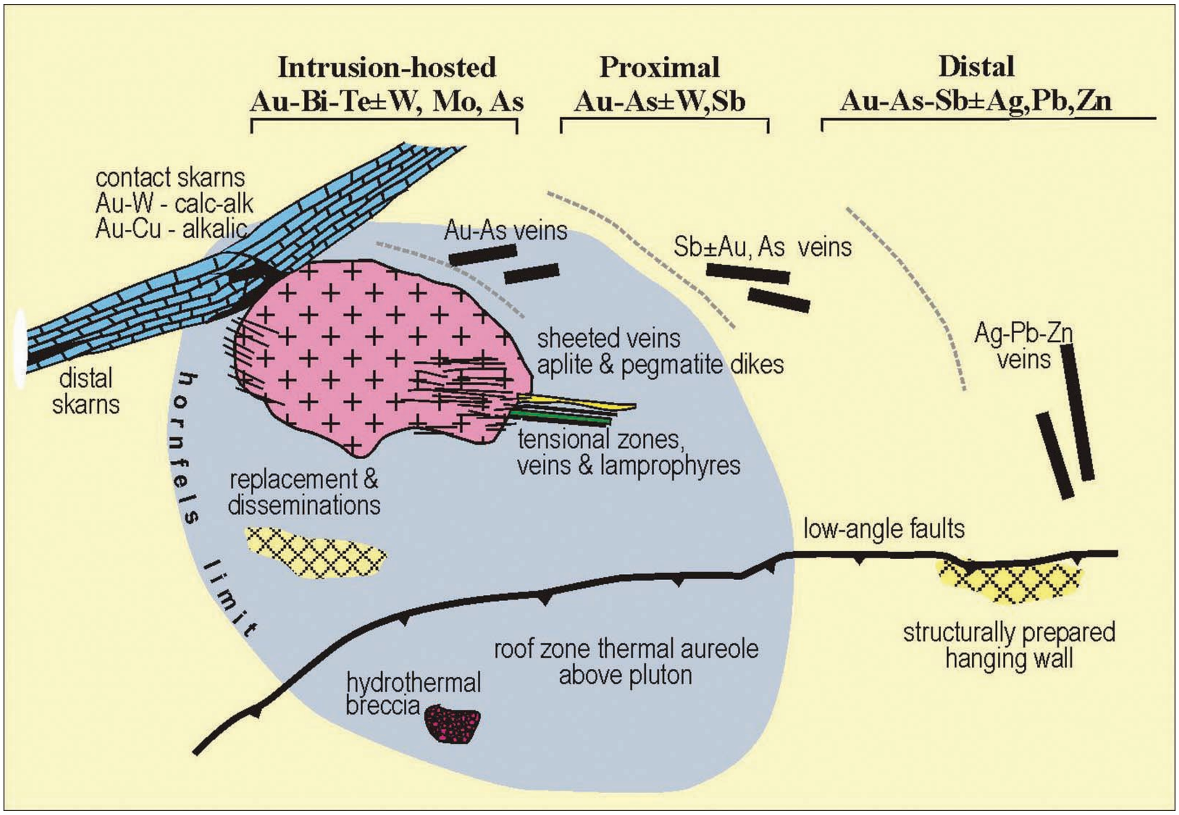

Fig. 1. General plan model of intrusion-related gold systems from the Tintina Gold Province. Note the wide range of mineralization styles and geochemical variations that vary predictably outward from a central pluton. From Hart et al. (2002).

Oxidation state

Plutons that are associated with gold mineralization in the TGP have a low primary oxidation state. The deposits are characterized by a low-sulphide (dd 5 volume %; often <1 volume %) reduced mineral assemblage dominated by pyrrhotite, locally containing loellingite, and typically arsenopyrite and pyrite, but no magnetite or hematite. Fluid inclusions locally contain methane. Plutons mostly contain ilmentite and titanite, and lack magnetite. Aeromagnetic responses are low. Magnetic susceptibility measurements average 0.15, but are all less than 0.5 x 10^{-3} SI units. The Fe_2O_3/FeO ratios are 0.15 to 0.3 and are mostly at or below the quartz-fayallite-magnetite (QFM) oxide buffer (Hart et al., 2004b).

Timing

Magmatism and associated mineralization are entirely post-orogenic, occurring at least 10 m.y. after peak metamorphism of rocks in the TGP. The gold deposits are associated with the last magmatic pulse in the belt, although the significance of this feature is not yet clear. Mineralization is the same age as the host or causative granite. Even with variations between isotopic systems, decay constants, and standards, most geochronological age data for deposits are within two million years of granitoid crystallization dates (Hart et al., 2004c).

Fluids

There is a wide variation in fluid inclusion compositions between deposits displaying mesozonal and epizonal characteristics. Deposits in shallow environments, with nonetheless high formation temperature (>350 °C), are characterized by an immiscible brine (>30 wt% NaCl equiv.) and low-salinity (< 5 wt% NaCl equiv.) vapor that commonly contains CO_2. Deposits of similar temperatures, but in deeper environments, contain abundant low-salinity (<10 wt% NaCl equiv.), CO_2-H_2O fluids, which in some deposits are post-dated by moderate to high salinity brines (10 to 40 wt% NaCl equiv.). These contrasting fluid types are interpreted as magmatic in origin, and to be the result of complex interplay between exsolution of different volatiles (carbon dioxide, water, and chlorine) from felsic melts at differing crustal levels (Baker, 2002).

Misclassified deposits?

The IRGS are the product of local-scale fluid convection that is likely derived from and driven by a cooling magmatic body, whereas orogenic gold deposits are widely considered to result from crustal-scale fluid flow likely derived from metamorphic dehydration (Groves et al., 1998; Stuwe, 1998). A number of deposits in regions dominated by orogenic gold deposits have been recently reinterpreted as belonging to the IRGS class or, at the very least and independent of classification, to be of magmatic origin. This is not entirely surprising because orogenic gold deposits typically form in regions where there is a broad spatial and temporal connection between orogenic/ metamorphic processes and granitoid magmatism (Groves et al., 1998; Goldfarb et al., 2001). For example, magmatic gold mineralization has been interpreted to be present among well-documented, turbidite-hosted orogenic gold systems in the western Lachlan fold belt of Victoria (Miller & Wilson, 2004; Bierlein & McKnight, 2005), in New Zealand's Otago region (de Ronde et al., 2000), and among the orogenic veins in the Meguma terrane of Nova Scotia (Kontak et al., 2004). Similarly, intrusion-related gold deposit models have been attributed to deposits in Archean orogenic gold camps. These include Wallaby (Hall et al., 2001) and some of the Golden Mile orebody (Walsh et al., 2003), both in the Eastern Goldfields province of the Yilgarn craton. Archean intrusion-related mineralization is also noted to be associated with syenitic intrusions in the Abitibi belt of Canada (Robert, 2001), and has long been considered by some workers to be related to felsic porphyries throughout the Superior Province (Card et al., 1989). Other Phanerozoic stated examples of intrusion-hosted gold, such as at Jiaodong (Wang et al., 1998) and along the northern margin of the North China craton (Nie et al., 2004), are considered to be genetically related to the host pluton. Even major deposits within the world's largest orogenic gold province of central Asian, such as Jilau (Cole et al., 2000) and Muruntau (Wall et al., 2004), have now been re-interpreted, in some cases, as having an intrusion-related origin.

These controversies in classification and genetic association are problematic, but are not surprising, as even key deposits within the TGP are controversial. Hart et al. (2002) suggested that this problem resulted from the inclusion of too many deposit types within a complex, single all-encompassing model and suggested a more-refined intrusion-related gold model that excluded deposits associated with shear zones and epizonal styles of mineralization. An intrusion-related classification for TGP deposits such as Donlin Creek (25 Moz; epizonal) and Pogo (7 Moz; shear zone-related), for example, was questioned and they were excluded from the model because they lack the distinguishing IRGS features. Both Pogo and Donlin Creek are instead considered by us to be orogenic deposits that are proximal to, or hosted by, approximately contemporaneous intrusive rocks (e.g., Groves et al. 2003; Goldfarb et al., 2004), but the debate on their classification and origin will likely continue (i.e. Smith et al., 1999; Rhys et al., 2003; Goldfarb et al., 2005).

Distinguishing features of IRGS

Intrusion-related and orogenic gold deposits share a large number of common characteristics. Despite the fact that the "reduced" IRGS model is pubescent and still evolving, the following distinguishing characteristics, derived from well-understood deposits, can be used to differentiate it from other gold deposit models:

Zoning-thermal gradients surrounding cooling plutons are steep, which results in concentric metal zones that develop outward for a few kilometers, or just beyond the thermal aureole, of a central mineralizing pluton. Orogenic gold deposits show little zoning, with the exception of Hg- and Sb-rich zones in their epizonal parts.

Diverse deposit styles-fluids exsolving from cooling plutons are opportunistic and cool quickly depositing metals in numerous available geological settings resulting in veins, stockworks, skarns, replacements etc, characterized by a wide range of gold grades, but with bulk minable volumes present at sub-gram grades (e.g., Fort Knox). Orogenic gold deposits lack such a diversity in style within a given lithology and commonly have consistent gold grades.

Sheeted veins-the most distinctive style of gold mineralization in IRGS are sheeted arrays of parallel, low-sulphide content, single stage quartz veins found over 10s to 100s of metres preferentially located in the pluton's cupola.

Metal associations –significant copper is lacking, associated plutons generate scheelite-rich hydrothermal systems, but gold doesn't correlate with tungsten in the gold deposits. Associated and gold-correlative Bi and Te geochemical signatures characterize intrusion-relate mineralization, but are also a feature of numerous hydrothermal deposit types and thus are not distinctive.

Pluton features-associated plutons have "smoking gun" characteristics that indicate generation of hydrothermal and mineralizing fluids. Physical features and geochemical support for characteristics such as high volatile contents, evidence of fractionation and fluid exsolution, associated skarns, presence of aplites/pegmatites, tourmaline veins, greisen alteration, and cupola-hosted mineralization.

Redox state-Reduced IRGS are associated with felsic, ilmenite-series plutons that lack magnetite, have low magnetic susceptibilities and low ferric:ferrous ratios <0.3. These types of plutons are uncommon in fore-arc settings, where orogenic gold deposits are most common.

Timing-deposits are coeval (±2 m.y.) with their associated, causative pluton. In contrast to orogenic gold deposits, IRGS develop subsequent to regional metamorphic and deformation episodes in the host allochthons.

Conclusions

Most mineral deposits are classified according to numerous empirically-derived characteristics. However, IRGS and orogenic gold systems share a large number of similar features (i.e., anomalous Bi, W, Te; reduced sulfide assemblages; low salinity, CO_2-bearing fliuids; post-peak-metamorphic lodes; spatial/temporal association with granitoids) that mostly result from their formation from fluids with similar compositions, and their formation in settings that both host large amounts of felsic magma. As a result, IRGS are furthermore better recognized using a set of distinguishing features that are particular to hydrothermal systems surrounding cooling magmatic bodies, which are distinctive from most orogenic gold systems.

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