WORLD-CLASS GREENSTONE GOLD DEPOSITS AND THEIR EXPLORATION

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Introduction

Greenstone terranes have been a major historical source of gold and host numerous world-class gold deposits, especially those of Archean age. Despite a long history of extensive prospecting and exploration efforts, these terranes still remain attractive exploration environments today, as illustrated for example by the high levels of exploration activities and recent discoveries in greenstone belts of Tanzania and West Africa. However, finding world-class deposits in these terranes is becoming increasingly challenging, in part because outcropping deposits have likely been discovered, at least in their most explored and most accessible portions. As a consequence, explorationists need to be more sophisticated through the use of better models and refined area selection criteria.

The many recurring characteristics of greenstone gold deposits led to the formulation of the "mesothermal" model, in which deposits are interpreted to at mid-crustal levels during compressional or tranpressional deformation (Colvine 1989; Groves et al. 1989; Hodgson 1993). However, significant departures from the type "mesothermal" model are also shown by a number of world-class deposits, both in terms of their settings and geological attributes. These atypical deposits have been explained by a variety of models, including porphyry, epithermal, and orogenic or crustal continuum models (Groves 1993; Kuhns et al. 1994; Penczak and Mason 1997; Groves et al. 1998).

The choice of appropriate models is of particular relevance in exploration, as it will generally dictate the sets of exploration criteria to be considered for area selection. The purpose of this document is to review the geological diversity that exists among greenstone gold deposits, and to discuss its significance in terms of models and some of the implications for exploration.

Variations among Deposits

As summarized by several workers (e.g. Hodgson 1993; Groves et al. 1998), recurring features of greenstone gold districts include their spatial association with crustal-scale fault zones, their occurrence at interfaces between major lithologic boundaries, the general greenschist grade of their host rocks, and the brittle-ductile nature of their host structures. Common attributes of the deposits themselves include the quartz-carbonate vein nature of mineralization and its significant vertical extent, their intimate association with second- and third-order compressional structures, the low sulfide content of the veins, the presence of zoned carbonate-sericite-pyrite alteration haloes, the high Au:Ag ratios and low base metal contents of their ores, and the involvement of low-salinity CO_2-bearing fluids enriched in K and S. Typical mesothermal deposits are further documented to have formed late in the deformation and metamorphic history of their host greenstone belt.

Departures from these type characteristics have been amply documented. In greenschist grade environments, some of these departures are readily explained in terms of *host-rock influence.* The presence of fuchsite, instead of sericite, in deposits hosted in ultramafic rocks, or the abundance of wallrock pyrite in magnetite-BIFs, are variations reflecting the chemical composition of the host rocks (e.g. Colvine 1989). Similarly, the dominance of veins in penetrative shear zones or in arrays of extensional veins reflects the competency of the host rock at greenschist conditions.

Departures in metamorphic grade of the host rocks have also been documented. In Western Australia, Archean gold deposits with mesothermal affinities occur in a variety of metamorphic settings, ranging in grade from sub-greenschist to upper amphibolite and even lower granulite. The deposits show variations in ore and alteration styles, which correlate with the metamorphic grade. These variations have been interpreted in terms of *differences in depth of emplacement* of the deposits (Groves 1993).

In other deposits, more significant departures in styles of mineralization and alteration have been documented (e.g. Allibone et al. 1998) and cannot be readily explained by variations on the mesothermal model. These distinct deposits have been explained in terms of *fundamentally different types of deposits*, including porphyry, epithermal and gold-rich VMS deposits, that have been overprinted by different degrees of metamorphism and deformation (Tourigny et al. 1993; Kuhns et al. 1994; Penczak and Mason 1997).

Finally, *distinct ages* of gold mineralization have been documented in a number of greenstone belts. In the Kalgoorlie district of Western Australia, Golden Mile-style mineralization is overprinted by Mt-Charlotte-style mineralization (Clout et al. 1990), with possibly as much as ~30 Ma between the two gold events (Kent and McDougall 1995). Similarly in the Val d'Or camp of the Abitibi greenstone belt, two distinct gold-quartz vein events are separated in time by at least ~10 Ma (Couture et al. 1994). The presence of multiple ages of gold mineralization is consistent with the recognition that some deposits have been overprinted by deformation and by metamorphism (see Robert and Poulsen 1997).

There is strong supportive evidence for all of the above interpretations, at least for selected deposits. In a number of other cases it is difficult to assess if a particular atypical deposit represents a shallow or a deep equivalent of a "mesothermal" deposit (i.e. an orogenic deposit) or rather represents another deposit type, possibly modified by subsequent deformation and metamorphism. Determining which scenario applies hinges heavily on a proper interpretation of the timing of mineralization relative to deformation and metamorphism. In general, this is a question that cannot easily be resolved without detailed field studies or precise geochronology.

Common Styles of Greenstone Gold Deposits

In an exploration program, emphasis is commonly placed on one particular model (or deposit type). In greenstone belt exploration, given the diversity in deposit characteristics and timings that is now recognized, it is important to be aware of other applicable models and of the range of deposit characteristics to be expected. For example, it is very useful to be able to determine which model is most applicable to a particular gold occurrence during its early evaluation.

The question of diversity among greenstone gold deposits has been approached by compiling and analyzing the geological characteristics of a many world-class greenstone gold deposits. This compilation shows that the deposits can be subdivided into coherent groups, or *styles of deposits*, on the basis of the nature and chemistry of the ore, the associated hydrothermal alteration, and the local geologic setting.

Table 1: Summary of characteristics of selected styles of world-class greenstone gold deposits, compiled from multiple sources.

DEPOSIT STYLE	QUARTZ-CARB. VEINS	DISSEMINATED SULFIDES	STOCKWORK VEINLETS	MASSIVE SULFIDES	CARBONATE-RICH VEINS
METAL ASSOCIATION	Au > Ag, W, B ± Te, Mo (Au:Ag = 5-10)	Au > Ag, As ± Te, Sb, Mo, Cu	Au:Ag variable, Cu Mo ± Bi	Ag < Au, Cu, As ± Zn, Pb, Te	Au > Ag, As, Sb, Zn ± Hg
NATURE OF OREBODIES	Discordant veins associated with shear zones; veins contain < 10% sulfides	Concordant to discordant zones of disseminated sulfides ± stockwork	Stockwork zones with intervening disseminated sulfides	Concordant to discordant massive sulfide lenses and veinlet zones	Carbonate-quartz veins and silica-sulfide replacement zones along faults
ORE-RELATED MINERALS	Quartz, carbonate pyrite, chlorite ± scheelite, tourmaline	Pyrite, chalco. ± arsenopyrite, tellurides, molybdenite.	Pyrite, chalco. ± molybdenite	Pyrite-chalco. ± sphalerite, arsenopyrite	Quartz, carbonate, arsenopyrite, pyrite, sphalerite, stibnite
COMMON ALTERATION MINERALS	Carbonate, sericite, albite ± biotite	(1) K-feldspar, sericite; (2) albite, carbonate, sericite	Biotite, amphibole, epidote ± sericite, carbonate	(1) sericite-chlorite (2) andalusite-sericite-kyanite	Biotite-carbonate, andalusite-sericite-chloritoid, and garnet-amphibole
SELECTED EXAMPLES	Kerr Addison Sigma-Lamaque, Victory, Plutonic, Globe and Phoenix, Ashanti	(1) Hemlo; (2) Malartic, Kanowna Belle, (Beattie, Ross)	Boddington, Las Cristinas Troilus McIntyre	(1) Horne; (2) Bousquet #2, Boliden	Campbell-Red Lake, Cochenour, Ankerite veins at Dome
APPLICABLE MODEL	Orogenic	Intrusion-related disseminated-stock.	Porphyry-like Au-Cu	Gold-rich VMS	Epithermal, low sulfidation type

Important styles of deposits represented by world-class examples include: quartz-carbonate veins, zones of disseminated sulfides, veinlet stockwork zones, massive sulfide bodies and carbonate-rich veins/siliceous replacements. Their main geological characteristics are summarized in Table 1 and reviewed below.

Deposits of the quartz-carbonate vein style are the most common worldwide. They consist of vein networks in moderately- to steeply dipping reverse shear zones and related extensional veins, vein arrays and breccia veins in competent lithologic units. In world-class examples, the vein networks have a surface fingerprint exceeding 1 km of strike length and they generally extend vertically down to depths of 1 km, and reaching 2 km in several deposits. World-class deposits of this style tend to occur in districts containing large proportions of mafic ± ultramafic volcanic rocks. At the deposit-scale, mineralization occurs in any rock-type present. The veins are composed mainly of quartz and carbonate, with smaller amounts of chlorite, scheelite, tourmaline, native gold and telluride minerals. Sulfide minerals consist mostly of pyrite, with some pyrrhotite and chalcopyrite. Despite their significant vertical extent, these deposits lack clear vertical mineral zoning. Wallrock alteration consists of carbonatization, sericitization, pyritization, and some albitization in several deposits, with higher temperature equivalent assemblages in amphibolite-grade deposits (Groves 1993).

Disseminated sulfide style deposits lack quartz-carbonate veins and rather consist of zones of 2-10% finely disseminated sulfides (mostly pyrite) with variably developed, but typically weak veinlet stockworks. In these deposits, mineralized zones are closely spatially associated with small felsic stocks and dykes intruded in clastic sedimentary rocks within the greenstone belts. The ores are gold rich and are enriched in As ± Sb, Te, Mo and Cu. There are however differences in hydrothermal alteration and ore chemistry among deposits of this group (Table 1). Hydrothermal alteration at Hemlo is dominated by K-feldspar and sericite, and the ores contain molybdenite, stibnite, realgar and orpiment, reflecting substantial enrichments in Mo, Sb, As and Hg. Alteration at Kanowna Belle and Malartic consists mainly of albite, sericite and carbonate. The ores at Kanowna Belle are only enriched in As, whereas those at Malartic also contain Te, Cu and Mo.

Stockwork veinlet style deposits consist of veinlet stockwork ores, with variable proportions of disseminated sulfides, spatially centered on epizonal stocks and dykes of intermediate to felsic compositions. There appears to be a gradation between deposits consisting of disseminated sulfides ± stockwork veinlets and those consisting of stockwork veinlets ± disseminated sulfides. However, those in which the orebodies are dominated by stockwork veinlets (of quartz or sulfides) are treated here as a different deposit style because of the contrasted alteration assemblages and ore chemistry (Table 2). World-class examples of this deposit style include Boddington, in Western Australia, Las Cristinas in Venezuela, the Troilus deposit in the Frotet-Evans greenstone belt.

A number of deposits consist of concordant to discordant lenses of massive sulfides, with some associated zones of sulfide-rich veinlets and disseminated sulfides. These include the world-class Bousquet-La Ronde and the Horne deposits in the Abitibi greenstone belt, and the Boliden deposit in the Skellefte district in Sweden. Like most others, deposits of this group are spatially associated with major fault zones or shear zones, at least on a regional scale. They occur in volcanic sequences containing a significant proportion of intermediate to felsic volcanic rocks. Orebodies are dominated by pyrite, but contain variable but significant proportions of chalcopyrite and arsenopyrite in some cases (Table 1). Deposits of this style are Ag-rich (Au/Ag < 1), with variable but generally significant concentrations As, Sb, Te, and Sn (Poulsen and Hannington 1996). The nature of hydrothermal alteration related to deposits of this group is variable. At Horne, silicification, sericitization and chloritization typical of base-metal rich VMS deposits have been documented. In contrast, the Bousquet and Boliden deposits occur in quartz-sericite and quartz-andalusite schists resulting from pre-metamorphic argillic to advanced-argillic alteration of volcanic rocks (Poulsen and Hannington 1996).

Finally, a few but important deposits represent a carbonate-rich vein style of mineralization, distinct in several ways from the quartz-carbonate vein style (see Table 1): the high-grade Campbell-Red Lake and the smaller Cochenour deposit in the Red Lake district, and the "ankerite veins" at the Dome mine in Timmins. These deposits occur in a sequence of Fe-tholeiite, komatiite, and minor felsic volcanic rocks, below a folded angular unconformity ("Timiskaming" unconformity) at the base of clastic sedimentary rocks. Mineralization consist of carbonate-quartz veins, with colloform to crustiform banding and cockade breccias, and sheeted veinlet zones, overprinted at Campbell-Red Lake by silica-sulfide auriferous replacement zones (Penczak and Mason 1997). The ore is gold-rich and is enriched in As, Sb, Zn, Hg, Mo, W. Associated hydrothermal alteration is complex: early alteration to carbonate, biotite and chlorite is overprinted by silicification and aluminous alteration characterized by variable abundances of andalusite, chloritoid, chlorite, garnet and amphibole (Penczak and Mason 1997).

Distribution and Timing of Different Deposit Styles

The distribution of deposits of different styles is not uniform along the crustal-scale fault zones and some districts or fault segments are dominated by specific deposit styles. In the Abitibi belt for example, deposits of the Bousquet district are of the massive sulfide style, those of the Malartic district are of disseminated sulfide style, whereas those of the Timmins, Kirkland Lake and Val d'Or districts are mainly of quartz-carbonate vein style. Despite significant provinciality in their distribution, world-class deposits of different styles also coexist with deposits of other styles in many districts or even deposits. A recurring feature of world-class deposits of nearly all styles, at least in Superior Province of Canada, is their close spatial association with folded, Timiskaming-type unconformities, as emphasized by Hodgson (1993).

Deposits of different styles also display different temporal relationships relative to penetrative deformation (typically D_2 increment of greenstone belt deformation) and to other geologic events. A majority of world-class quartz-carbonate vein deposits can be shown to have formed during D_2, in active reverse to reverse-oblique shear zones and related D_2 structures (e.g. Foster 1989; Robert and Poulsen 1997). Two ages of quartz-carbonate vein style mineralization have been documented in the Val d'Or district of Abitibi (Couture et al. 1994) and in the Kalgoorlie district of Western Australia (Clout et al. 1990). In Kalgoorlie, Golden Mile-style shear-hosted veins related to D_2 structures are overprinted by later Mt-Charlotte-style vein arrays related to D_3.

In contrast, many disseminated sulfide and stockwork styles of deposits have been overprinted by D_2 structures and foliation, as at Hemlo (Robert and Poulsen 1997). Some deposits of this style, such as Malartic, are intimately associated with high-level intrusions of Timiskaming age, emplaced in already tilted rocks (i.e. after D_1 deformation) and may be temporally related to such intrusions and to the Timiskaming "event" in a general sense. The stockwork style Boddington deposit formed very late in the evolution of its host greenstone belt (Allibone et al. 1998) and represents a notable exception. Carbonate-rich vein style mineralization at Timmins and Red Lake occupy D_1 structures and are overprinted by the D_2 penetrative foliation (Penczak and Mason 1997). They may also be related to a Timiskaming "event". Known examples of massive sulfide style mineralization systematically predate development of penetrative S_2 foliation and D_2 deformation. Strong arguments can also be made for gold being deposited contemporaneously with the sulfides (see Robert and Poulsen 1997).

World-class gold deposits have thus formed at several stages during the evolution of greenstone belts. As shown for Southern Abitibi (Fig. 1), they have formed (1) during early stages of volcanism (Bousquet, Horne), (2) after D_1, during a Timiskaming stage of renewed high-level alkalic plutonism (Malartic; ankerite veins at Dome), and (2) after folding of Timiskaming sedimentary rocks and during D_2 shortening of the greenstone belts (Sigma-Lamaque). In other belts, quartz-carbonate vein deposits have also formed during D_3, for example at the Mt-Charlotte deposit in Western Australia (Clout et al. 1990).

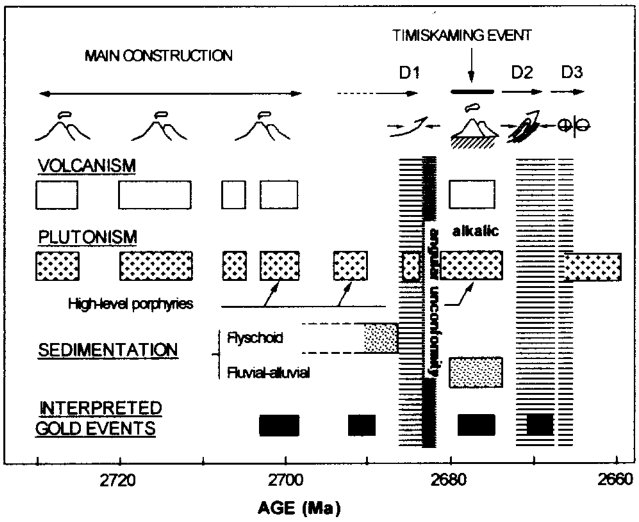

Figure 1: Interpreted main stages of gold mineralization in Southern Abitibi belt. See Robert (in press) for details.

Applicable Models

The range of hydrothermal characteristics and multiple ages of formation of the different styles of greenstone gold mineralization must reflect fundamental differences in their processes of formation. Some variations in ore composition and alteration assemblages (Table 1) can be explained by variations in P-T conditions of mineralization by a fluid of relatively uniform composition (Mickuki and Ridley, 1993). However, such contrasting assemblages as carbonate-sericite-albite, K-feldspar-sericite, and andalusite-kyanite-sericite require the involvement of fluids of significantly different compositions. This supports the existence of fundamentally different types of gold deposits in greenstone belts and requires consideration of multiple models.

Models applicable to diverse deposit styles are listed in Table 1. The orogenic model obviously applies to quartz-carbonate vein deposits in greenschist-grade terranes and to similar vein deposits in amphibolite-grade terranes. Deposits of the massive sulfide style are readily explained in terms of gold-rich VMS deposits. A shallow-marine high-sulfidation epithermal model (Poulsen and Hannington 1996) should also be considered for those with argillic or advanced argillic-type alteration (e.g. Bousquet). Deposits of the disseminated sulfide and stockwork veinlet styles have affinities with magmatic-hydrothermal deposits formed in the porphyry environment, although few world-class examples, if any, have definite characteristics of porphyry-type deposits. Many of these deposits are best fit the class of "stockwork, disseminated and replacement deposits in non-carbonate rocks" as defined by Sillitoe (1991). Finally, a low-sulfidation epithermal model adequately explains the characteristics of the carbonate-rich vein styles of deposits. Clearly, models for Phanerozoic gold deposits in volcano-plutonic arcs are applicable to greenstone terranes.

Selection of an appropriate model should be based on several, rather than a single, aspects of deposit considered, as some variations may be simply due to the influence of host rocks. For example, basalt-hosted quartz-carbonate vein mineralization may change to a stockwork veinlet zone where the host structure intersects a competent felsic intrusion. Despite the change in style of ore, its composition and associated alteration will nevertheless be characteristics of the quartz-carbonate style of mineralization.

Implications for Exploration

The existence of a number of fundamental types of world-class gold deposits requires consideration of multiple sets of criteria in greenstone gold exploration. This has several important implications for exploration.

First, gold deposits of different types will occur in different lithologic settings within greenstone belts. For example, gold-rich VMS deposits occur in areas of abundant felsic volcanic rocks, porphyry-style Au-Cu deposits in association with intermediate to felsic subvolcanic intrusions, and quartz-carbonate veins in areas of abundant tholeiitic basalt. Second, because of differences in ore styles ore composition and hydrothermal alteration, different deposit types will have different manifestations in the field. They will also have distinct geochemical and geophysical responses and patterns. Third, deposits that formed late in the evolution of greenstone belts are likely to have retained their primary morphologies. Deposits formed prior to D_2 are likely to be tilted, resulting in distinct alteration zoning patterns (at least for porphyry-style deposits), and/or to be strained, resulting in modified morphologies (e.g. elongated parallel to extension lineation in areas of high strain).

Nevertheless, some exploration criteria will be common to many of the deposit types considered, especially structural ones, as fluid flow and emplacement of intrusions will be strongly influenced by fault and shear zones. Common criteria include the proximity to crustal-scale faults, more specific siting in higher-order structures, and proximity to folded angular unconformities and Timiskaming-type sedimentary successions.

In conclusion, it is believed that consideration of multiple models and multiple sets of criteria will be an important key to future gold exploration successes in greenstone belts.

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