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The Late-Archean Magmatic Gold Event: Toward a Non-Uniformitarian Approach

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Abstract. Gold is exceptionally abundant at the end of Archean. Three main steps are recognized: (1) a late TTG event at the core of calderas, producing small porphyries and gold-rich VMS deposits; (2) a sanukitoïd event, producing alkaline and felsic subvolcanic plutons with large gold hydrothermal systems, and (3) a hydrothermal/structural event. A large part of the gold mineralization may be directly related to the unique geodynamic situation, including the first subduction with two generations of gold-enriched intrusions.

Keywords. Gold deposits, Geodynamic, Archean.

1 Introduction

The end of Archean was a key period for crustal construction; more than 50 % of the volume of the continental crust were formed. It is also an exceptional period for gold concentrations as more than 50 % of the world's gold resources are hosted by sedimentary and volcanic rocks of late-Archean age (Goldfarb et al., 2005). Gold has been mainly exploited from clastic sedimentary units, shear zones (orogenic gold deposits), gold-rich polymetallic volcanogenic massive sulfide deposits and disseminated zones around pluton.

Until now, most of the interpretations related to this major metallogenic period have favoured an uniformitarian approach (Kerrich et al. 2000). Most of the Archean gold deposits have strong similarities with Phanerozoic deposits of the same class, and their interpretation does not imply major differences in the volcanic or structural environment. The only exception would have been the Witswaterand gold-rich basin where almost no recent equivalents are known (Phillips and Powell 2015).

However, most of these interpretations rely on the assumption that the geodynamic processes during the Archean were similar to the present time plate tectonics regime (Kerrich et al. 2000). Most of the interpretations do recognize however that Earth was different: the atmosphere was lacking of oxygen, the ocean composition was reduced, life was not a major component of the geochemical cycle. Moreover, several key elements of the present time plate tectonic regime were lacking such as true ophiolite and high grade metamorphic belts. Mantle dynamics were also different, due to the higher geothermal gradient and its primitive composition. Ongoing debates argue about the first occurrences of recognizable plate tectonics style processes, from 3.2 to 2.6 (Bédard 2013; Wyman 2013).

It is therefore far from certified that the metallogeny of gold at the end of Archean would have been similar to the gold mineralisation episodes in the Proterozoic and Phanerozoic. The gold cycle could have been very different because of the high geothermal gradient that was changing the mechanical properties of the crust, because of the different composition of the lithospheric mantle and therefore because of a different magmatism.

In this paper, we will review some specific aspects of gold deposits in the Abitibi greenstone belt, the world's largest Archean greenstone belt, emphasizing the magmatic connections of a large number of deposits. This concept has gain in importance as the largest producing gold deposits presently mined in Canada and Australia since 2012 are respectively Malartic (Abitibi belt) and Boddington (Yilgarn block), both associated with late Archean intrusive rocks.

2 Late Archean gold deposits in the Abitibi greenstone belt

Gold occurs in a variety of deposit styles in the Abitibi Greenstone Belt (AGB). Archean gold (copper-molybdenum) porphyry deposits have long been described in the Superior Craton (Ayers and Cerny 1982). Volcanogenic Massive Sulphide (VMS) deposits show major enrichment in gold. Gold shear zones are archetypal of the AGB, and several gold deposits are associated with alkaline intrusions. Minor deposits may show also an association with BIF (Chimo), black shales (Telbel) or within an epithermal environment (Selbaie B zone, Géant Dormant). Geological environment and detailed geochronological studies allow recognition of three main periods of gold deposition, associated with the volcanic arc construction, and with two main deformation events.

2.1 Volcanic arc construction

The magmatic arcs of the Abitibi greenstone belt have been constructed between 2735 and 2696 Ma (Mueller et al. 2009). Two main lithologies dominate, thick bimodal volcanic series and subvolcanic tonalite-trondjemite-granite (TTG) suites forming subconcordant bodies of limited extension (Galley 2003). The felsic volcanism that hosts VMS mineralization are chemically and temporally related to the TTG (Huston 2000). Gold is associated with both environments, and TTG have been considered as the possible source of metal for VMS (Poulsen and Franklin 1981).

In the Northern Zone of the AGB, the Chibougamau district displays many styles of mineralization (Pilote 1998) from zoned porphyries to more distal vein systems. The main Cu-Au vein-hosted ores present an assemblage of pyrrhotite, chalcopyrite, pyrite, magnetite and gold that reflect an oxidising environment of deposition. The porphyry-style Mop2 deposit shows disseminated facies with a more reduced assemblage and an alteration zoning similar to Phanerozoic equivalents

(Lépine 2008). Several other Au or Cu-Au prospects with porphyritic facies have been encountered in the Northern Zone of the AGB, such as in the Selbaie district where a pyritic massive sulphide deposit is associated with a rhyolitic volcanic sequence characterized by porphyritic dykes and epithermal mineralisation (Faure et al. 1996).

In the Southern Zone of the AGB, polyphased calderas of the Blake River district also display several porphyry-style occurrences, (Pearson and Daigneault 2009). At Don Rouyn (QC), chalcopyrite-chalcocite concentrations are surrounded by a hematitic halo. The St-Jude breccia is an example of breccia pipe dated at 2696.6 ± 0.9 Ma (McNicoll et al. 2014) indicating that they were emplaced at the very end of the Blake River Group volcanism. In the Doyon-Bousquet-LaRonde camp (QC), the intrusion-hosted Au ± Cu (5 Moz) Doyon deposit is associated with the Mooshla Intrusive Complex (Dubé et al. 2007). The recent large Coté Lake (ONT) discovery is associated with magmatic-hydrothermal breccia and disseminated pyrite and chalcopyrite. Re-Os dating indicate that it is coeval with an early tonalitic event at 2737 Ma (Kontak 2012)

These synvolcanic gold porphyry deposits in the AGB share several characteristics: an association with surficial magmatic chambers in tonalitic volcanic complexes; a relation with post-cauldron resurgence; the presence of Cu and Mo and an oxidizing depositional environment characterized by the presence of magnetite and hematite; a poorly developed potassic alteration; and a shallow level of emplacement in an underwater environment, without large boiling and fluid concentration;

Most of these synvolcanic intrusions are associated with bimodal volcanic sequences that also host gold-rich VMS deposits. The most important ones are located in the Southern Abitibi Zone such as the Horne and Laronde districts, in the Black River Group. In this latter district, gold is present in Au-rich sulphide stockworks and disseminations (e.g., Bousquet 1 deposit), Au-rich VMS systems (LaRonde Penna, Bousquet 2-Dumagami) and Au-Cu quartz-sulphide veins that are possibly genetically related to the Mooschla intrusion (2698-2697 Ma), where several stages of volatiles exsolution have been observed (e.g., Doyon deposit; Galley and Lafrance 2014).

Although largely debated, field evidence (Mercier-Langevin et al. 2014) and isotopic dating indicate that tonalitic porphyries and VMS deposits are sub-contemporaneous and reflect two expressions of magmatic-hydrothermal activity related to the late uplift of sub-marine calderas.

2.2 First Deformation Event

After the formation of large calderas, uplift continued and the first detrital sedimentation occurred in sedimentary basins along the major fault zones. The interpretation of this uplift remains uncertain as evidence of normal, strike-slip and reverse movements have been observed along the major breaks.

Syntectonic gold-rich porphyries are related to this tectonic phase (2686-2661 Ma), synchronous with the formation of detrital basins along major breaks (Porcupine and Temiskaming sediments). Most of the deposits are located near or within sediments and are associated with small alkaline intrusions of monzonitic to syenitic composition. They may form multiple plugs and breccia pipes, more or less elongated (Legault and Lalonde 2009). They present a large spectrum of composition, from oxidized mafic (pyroxene-amphibole) to felsic intrusions. Fe- enrichment occurs both at the magmatic and hydrothermal stages. Trace element signatures allow clear distinction between a sanukitoid clan (Laurent et al. 2014), represented by mafic intrusion with a bull-eye magnetic signature (Hattori, 1987), from a more felsic/alkalic clan, with a doughnut shape magnetic anomaly. These two styles derive from the same oxidized magmatism, with different degree of evolution (Fayol et al. submitted).

Numerous occurrences have been discovered and mined along the major breaks of the AGB (Robert, 2001). Along the Cadillac Larder-Lake Fault zone, syenite-related gold mineralization has been recognized in the Young Davidson, Kirkland Lake, Upper Canada, Upper Beaver and Kerr Addison districts in Ontario, and in Francoeur-Wasamac, Baie Renault, Canadian Malartic and Camflo districts in Québec. These deposits total more than 1200 t of gold. Along the Destor Porcupine Fault Zone, syenite-related gold mineralization has been recognized in West Timmins, Black Fox, Canadian Arrow (Ontario) and Beattie (Quebec). More than 200 t of gold are related to the alkaline magmatism along these fault zone. Gold with alkaline intrusion have also been recognized in other large deformation zones such as the Casa-Berardi E-W corridor (Douay) and the Wedding-Lamarck NE-SW deformation zone with the Lac Bachelor and Lac Short deposits.

The emplacement of these alkaline rocks spans from the end of the tonalitic magmatism to the onset of crustal melting, represented by high-Al leucogranite (2669-2639 Ma). The Timmins district is slightly older than most of the other districts (2691-2687 Ma, Bleeker 2012) and could belong to the end of the TTG suites.

Au-rich alkaline intrusion-associated mines and prospects share numerous characteristics (Robert, 2001): they consist of disseminated sulphides and stockworks of quartz, with zones of carbonate, albite, K-feldspar and sericite alteration; their metal association is characterized by Cu, As and Te with variable amounts of Pb, Zn, Ag, Hg, Mo, Bi, W and Sb. Anhydrite, hematite, fluorite, tourmaline and scheelite have also been recognized in several of these deposits. Both anhydrite and hematite are indicative of relatively high fO_2, which is corroborated by the negative isotopic value of the sulphur in the pyrite.

The precise relationships between magmatic systems and gold is still strongly debated. On one hand, the strong spatial and temporal association, field studies and some isotopic results demonstrate a contemporaneity of magmatic and hydrothermal system such as in the Lac Bachelor deposit (Fayol et al. 2013) or in the Beattie mine (Bigot and Jébrak 2015). On the other hand, the late emplacement of the richest gold veins and isotopic dating in Timmins and Malartic suggest that gold mineralization could have been up to 30 My younger

than the intrusion (Helt et al. 2014). More works is therefore require to better understand the role of early and late events in the formation of these gold deposits.

2.3 Second Deformation Event

The second deformation event represent both a vertical (reverse and normal?) increment of deformation and a transcurrent dextral shear along the Cadillac break. This brittle ductile deformation is contemporaneous with the emplacement of numerous orogenic gold deposit such as Sigma-Lamaque, Lapa, McWatter in Quebec and Kirkland Lake, Larder Lake, Detour Lake, Dome, Pamour in Ontario. These deposits have been carefully studied since 30 years and have been attributed to the orogenic gold model (Colvine 1989; Groves et al. 1998). A majority of workers have relate their ore genesis to processes of crustal devolatilization as indicated by the CO_2-H_2O composition of the hydrothermal fluids, the progressive decrease in concentration of elements enriched in the gold deposits with increasing metamorphic grade of the country rocks, and the common association of ores with medium-grade metamorphic environments. Yet, significant debate continues in order to understand the origin of these deposits (Goldfarb et al. 2005).

Detailed studies both in the Abitibi and the Yilgarn block of Western Australia have shown that this class is rather heterogeneous, with multiple ages of emplacement (Duuring et al. 2007; Rafini 2013). Some are associated with plutonic stocks whereas some others do not show any relation with magmatism. In the sedimentary environment, a continuity has been demonstrated from syn-sedimentary gold concentration to epigenetic deposits (Large et al. 2011). The study of the Beattie deposit shows that the same continuity could be observed for magmatic gold concentration in the Abitibi (Bigot and Jébrak 2015). These results suggest that the source of gold could be of different origins, at different crustal level, from deep metamorphic mobilization to local reconcentration. Late H_2O-CO_2 fluids have been observed in most of the orogenic belts, from Archean to present. For instance, in the Apennine belt, H_2O-CO_2 fluids are strongly associated with the seismicity; their chemistry results from local equilibration with the host rock although their gas content come from the underlying mantle (Agostinetti et al. 2011). Orogenic gold deposits may mainly indicate the presence of previous gold enrichment remobilized during subsequent deformation, metamorphism and hydrothermal fluid circulation. The distance of migration is therefore a key element to be addressed.

3 Geodynamics of gold in the Late Archean

Gold deposition occurs early during the AGB arcs construction processes, associated both with plutonic and volcanic rocks. The association of gold with copper and molybdenum and the similarities of the late Archean systems with modern ones suggest that gold enrichment is related to the magmatic evolution itself. The geochemical signatures of the TTG complexes (Galley and Lafrance 2014) are typical of I-type calc-alkaline magmas belonging to the magnetite series, indicating that they were formed by melting of igneous rocks. Their average content in traces elements indicates that these subvolcanic TTG belong to the low-pressure sodic family of TTG (<12 kbar), near the garnet-in limit, coexisting with a plagioclase+pyroxene(s) ± amphibole in which a moderate amount of magnetite crystallization has taken place (Moyen 2011; Galley and Lafrance 2014). They appear very similar to plagiogranites /dacites found in a mid-ocean ridge or oceanic plateau setting. Such magmatism could be produced by partial melting of hydrous mafic rocks at the base of a thick crust or mafic plateaus, or by a flat subduction.

The second step of concentration is associated with the sanukitoïd magmatism. These K-Mg enriched rocks probably result from mantle-crust interactions (Martin et al. 2009). Sanukitoïds formation requires a mechanism to carry crustal rocks (TTG, sediments) down into the mantle (Van Huten and Moyen 2012), Isotopic data indicate that the subducting slab did not contain old cratonic material and that the mantle metasomatism took place shortly before the alkaline magmatism, probably during the tonalitic event (Hattori et al. 1996). The presence of ethane in the fluid could indicate a source from organic-rich sediments (Gaboury 2013). High temperature gradients would imply a flat subduction setting. Re-melting of previously gold-enriched magma is known to increase the gold content of the magma (Jégo and Pichavant 2012). Therefore, the melting of gold-enriched previous TTG (and sediments?), appears to be the most probable mechanism for gold enrichment in late-Archean sanukitoïds.

The third step of concentration is illustrated by the numerous “orogenic” type gold deposits. Several systems have been recognized along the Cadillac break (Rafini 2013) and show different styles of deformation and mineral association type. They are the reflections of the many syntectonic hydrothermal systems that record the circulation of H_2O-CO_2 fluid at the end of the orogeny.

4 Conclusions

The construction of the Abitibi gold belt results from the formation of different styles of deposits during three main events:

(1) an early juvenile tonalitic magmatic/ hydrothermal event, sharing numerous similarities with present-time tonalitic gold porphyries;
(2) a sanukitoïd magmatic-hydrothermal event, that could be the result of the first subduction event on Earth;
(3) a late structurally-controlled hydrothermal system.

Gold deposits of different type and age are located in the same area, defining a "provinciality" (Huston 2000). It could have come either by consanguinity or by inheritance from the same TTG.

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