Gold-rich Volcanogenic Massive Sulphide Deposits

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Abstract

Gold-rich volcanogenic massive sulphide deposits (Au-rich VMS) form a subtype of both volcanogenic massive sulphide and lode-gold deposits. Their diagnostic features are stratabound to discordant, volcanic-hosted massive sulphide lenses with associated discordant stockwork feeder zones in which average Au grades (in g/t) exceed associated combined Cu, Pb, and Zn grades (in weight percent); Au is thus the main commodity. The Au-VMS deposits are present in both recent seafloor and deformed and metamorphosed submarine volcanic settings. They occur in a variety of volcanic terranes from mafic bimodal through felsic bimodal to bimodal siliciclastic in greenstone belts of all ages, typically metamorphosed to greenschist and lower amphibolite facies, and intruded by subvolcanic intrusions and dyke-sill complexes. The deposits are commonly located in proximity of intermediate to felsic volcanic centres, at or close to the interface between intermediate to felsic volcanic domes and basalt-andesite or clastic sediments. Several of the largest Au-VMS deposits are located in Canada: Horne, Bousquet 2-Dumagami, LaRonde Penna, and Eskay Creek. The first three deposits are hosted within the Archean Blake River Group, which is therefore an important geological assemblage for this style of Au deposit.

In metamorphosed greenstone terranes, the gangue minerals may include quartz, sericite, aluminous silicates, such as andalusite, kyanite, pyrophyllite, and Zn-rich staurolite, and Mn-rich garnet. Sulphide minerals are mainly pyrite and base-metal sulphides with a complex assemblage of minor phases including bornite, tennantite, sulphosalts, arsenopyrite, mawsonite, and tellurides. The Au has most commonly an uneven distribution within the deposit due to both primary depositional controls and subsequent tectonic remobilization. The chemical signature of the ore is diverse, and dominated by Au, Ag, and Cu or Zn with locally high concentrations of As, Sb, Bi, Pb, Se, Te, and Hg. The Eskay Creek deposit is a low-temperature Au-rich VMS deposit characterized by a mineralogical assemblage of stibnite, realgar, cinnabar, and arsenopyrite with various proportions of barite. It is clearly distinct from other Au-rich VMS deposits. Potassic alteration characterized by K-feldspar, typical of deposits with an Au-Zn-Pb-Ag association, occurs at Eskay Creek, especially in the footwall alteration zone. The advanced argillic alteration found at LaRonde Penna and Bousquet 2-Dumagami is thought to be typical of deposits from the Au-Cu association. Where present, the metamorphosed advanced argillic and more discrete massive silicic alteration assemblages indicate high-sulphidation conditions similar to those encountered in some epithermal environments.

There are two genetic models for Au-rich VMS: 1) conventional syngenetic volcanic-hosted Au-poor VMS mineralization overprinted during regional deformation by Au mineralization; and 2) syngenetic VMS deposits characterized by an anomalous fluid chemistry (with magmatic input) and/or deposition within a shallow-water to subaerial volcanic setting equivalent to epithermal conditions, in which boiling may have had a major impact on the fluid chemistry. The deformation and metamorphism that commonly overprint the mineralization in ancient terranes have obscured the original relationships and led to considerable debate about the syntectonic versus synvolcanic origin of Au-rich VMS.

Résumé

Les gîtes de sulfures massifs volcanogènes riches en or (SMV riches en Au) constituent un sous-type des gîtes de sulfures massifs volcanogènes (SMV) ainsi que des gîtes d'or primaires. De manière caractéristique, ils consistent en lentilles stratoïdes à discordantes de sulfures massifs encaissées dans des roches volcaniques, lesquelles surmontent des zones nourricières discordantes formées d'un enchevêtrement de filonnets minéralisés (stockwerk). Les valeurs de la teneur moyenne en or (en g/t) de ces minéralisations excèdent celles des teneurs combinées en Cu, Pb et Zn (en pourcentage); l'or constitue donc la principale substance utile de ces gîtes. Les gîtes de SMV riches en Au sont présents aussi bien dans des environnements volcaniques des fonds marins actuels que dans des environnements volcaniques plus anciens où les roches sont déformées et métamorphisées. Ils se retrouvent dans toute une gamme de terrains volcaniques, des successions mafiques aux successions bimodales à dominante felsique et jusqu'aux empilements de roches volcaniques bimodales et de roches silicoclastiques des ceintures de roches vertes de tous âges, métamorphisées de manière caractéristique au faciès des schistes verts ou au faciès des amphibolites inférieur, dans lesquelles se sont mis en place des intrusions subvolcaniques et des complexes de dykes et de filons-couches. Les gîtes se trouvent couramment à proximité de centres volcaniques de composition intermédiaire à felsique, à l'interface, ou à proximité de l'interface, entre des dômes de roches volcaniques intermédiaires à felsiques et des successions de basalte-andésite ou de roches sédimentaires clastiques. Plusieurs des plus grands gisements de SMV riches en Au se trouvent au Canada : Horne, Bousquet 2-Dumagami, LaRonde Penna et Eskay Creek. Parmi ceux-ci, les trois premiers sont encaissés dans le Groupe de Blake River d'âge Archéen, lequel constitue par conséquent un important assemblage géologique pour ce style de gîte aurifère.

Dans les terrains métamorphiques de roches vertes, les minéraux de gangue peuvent comprendre le quartz, la séricite, des silicates alumineux comme l'andalousite, la kyanite, la pyrophyllite et la staurotide riche en Zn, ainsi qu'un grenat riche en Mn. Les minéraux sulfurés sont principalement la pyrite et des sulfures de métaux communs avec une association complexe de phases mineures incluant la bornite, la tennantite, des sulfosels, l'arsénopyrite, la mawsonite et des tellurures. L'or présente en général une distribution inégale dans le gîte en raison à la fois de contrôles primaires

Dubé, B., Gosselin, P. Mercier-Langevin, P., Hannington, M., and Galley, A., 2007, Gold-rich volcanogenic massive sulphide deposits, *in* Goodfellow, W.D., ed., Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p. 75-94.

sur la formation de la minéralisation et de la remobilisation tectonique subséquente. La signature chimique du minerai peut prendre diverses formes et elle est dominée par Au, Ag et Cu ou Zn avec par endroits des concentrations élevées de As, Sb, Bi, Pb, Se, Te et Hg. Le gisement d'Eskay Creek est un gîte de SMV riches en Au de basse température, caractérisé par une paragenèse de stibine, réalgar, cinabre et arsénopyrite avec diverses proportions de barytine. Il se distingue nettement des autres gîtes de SMV riches en Au. Au gisement d'Eskay Creek, on peut observer une altération potassique, caractérisée par la présence de feldspath potassique et typique des gîtes présentant une association Au-Zn-Pb-Ag, surtout dans la zone d'altération de l'éponte inférieure. L'altération argileuse acide aux gisements de LaRonde Penna et de Bousquet 2-Dumagami serait caractéristique des gîtes présentant l'association Au-Cu. Lorsque présentes, les associations de minéraux témoignant du métamorphisme de zones d'altération argileuse acide ou de zones de silicification massive plus discrètes révèlent des conditions indicatrices d'une forte activité en soufre similaires à celles observées dans certains milieux épithermaux.

Il existe deux modèles génétiques pour les gîtes de SMV riches en Au : 1) minéralisation syngénétique classique de SMV pauvres en or dans des roches volcaniques à laquelle s'est superposée une minéralisation en Au lors de la déformation régionale; et 2) gîtes syngénétiques de SMV caractérisés par une composition chimique anomale des fluides (avec apport magmatique) ou par le dépôt dans un cadre volcanique en eau peu profonde ou subaérien où les conditions sont équivalentes à celles des gîtes épithermaux, dans lesquelles l'ébullition peut avoir une incidence majeure sur la composition chimique des fluides. La déformation et le métamorphisme, dont les effets se superposent à la minéralisation dans les terrains anciens, ont obscurci les relations originales et suscité un débat considérable sur l'origine syntectonique ou synvolcanique des gîtes de SMV riches en Au.

Definition

Simplified Definition

A lens of Fe-, Cu-, Zn-, and Pb-sulphides, with significant amounts of Au and Ag, formed on or below the seafloor from fluids vented on and around submarine volcanoes.

Scientific Definition

Gold-rich volcanogenic massive sulphide (Au-rich VMS) deposits form a subtype of both volcanogenic massive sulphide (VMS) and lode-Au deposits (Poulsen and Hannington, 1996; Hannington et al., 1999; Huston, 2000; Poulsen et al., 2000) (Fig.1). Like most VMS deposits, they consist of semimassive to massive, stratabound to locally discordant sulphide lenses underlain by discordant stockwork feeder zones. The main difference between Au-rich VMS and other VMS deposits is their average Au content (in g/t), which exceeds the associated combined Cu, Pb, and Zn grades (in weight percent) (Poulsen et al., 2000). Gold is thus the main commodity; however, the polymetallic nature of this deposit subtype makes it more resistant to fluctuating metal prices, resulting in a very attractive exploration target. Several Au-rich VMS deposits discussed by Hannington et al. (1999) and Huston (2000) are not included within this subtype of Au deposits as their Au to base metal ratio is too low. Furthermore, the focus of the following text is mainly on Canadian examples and particularly those deposits found in the Archean Abitibi greenstone belt. For a complete global perspective the readers are referred to Large et al. (1989), Poulsen and Hannington (1996), Sillitoe et al. (1996), Hannington et al. (1999), Huston (2000), and Franklin et al. (2005), among others.

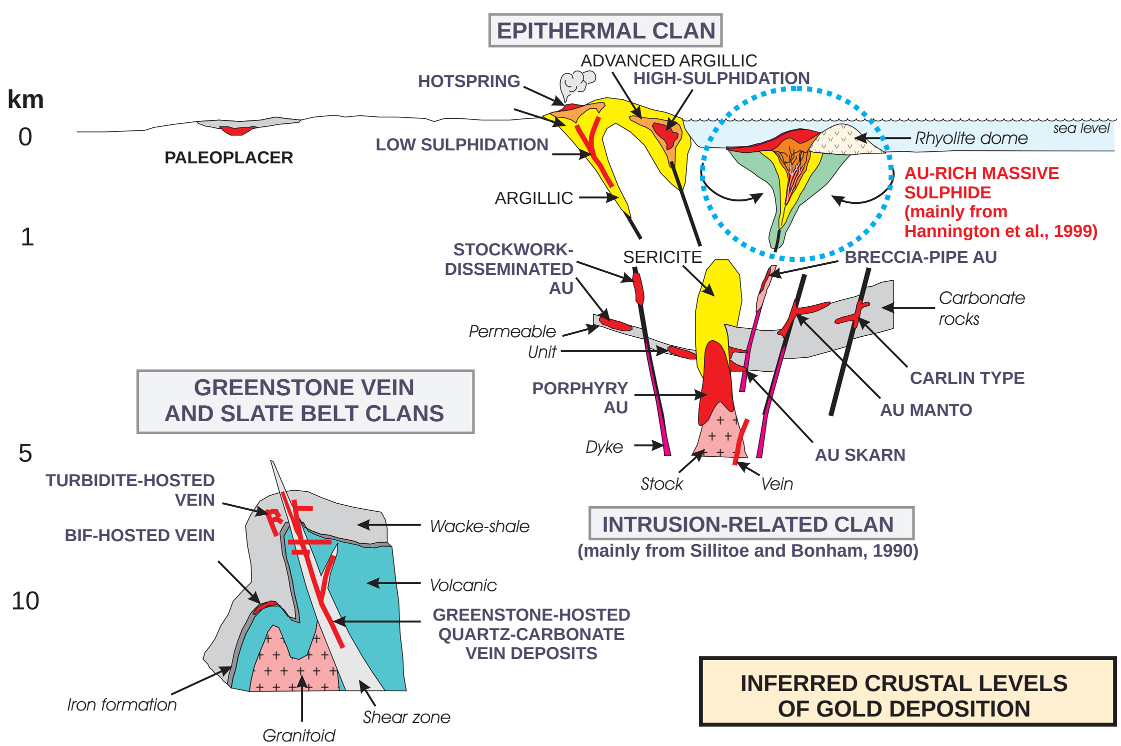

Figure 1. Schematic illustration of the various types of gold deposits shown at their inferred crustal levels of formation (Dubé et al., 2001, modified from Poulsen et al., 2000). BIF=banded iron formation.

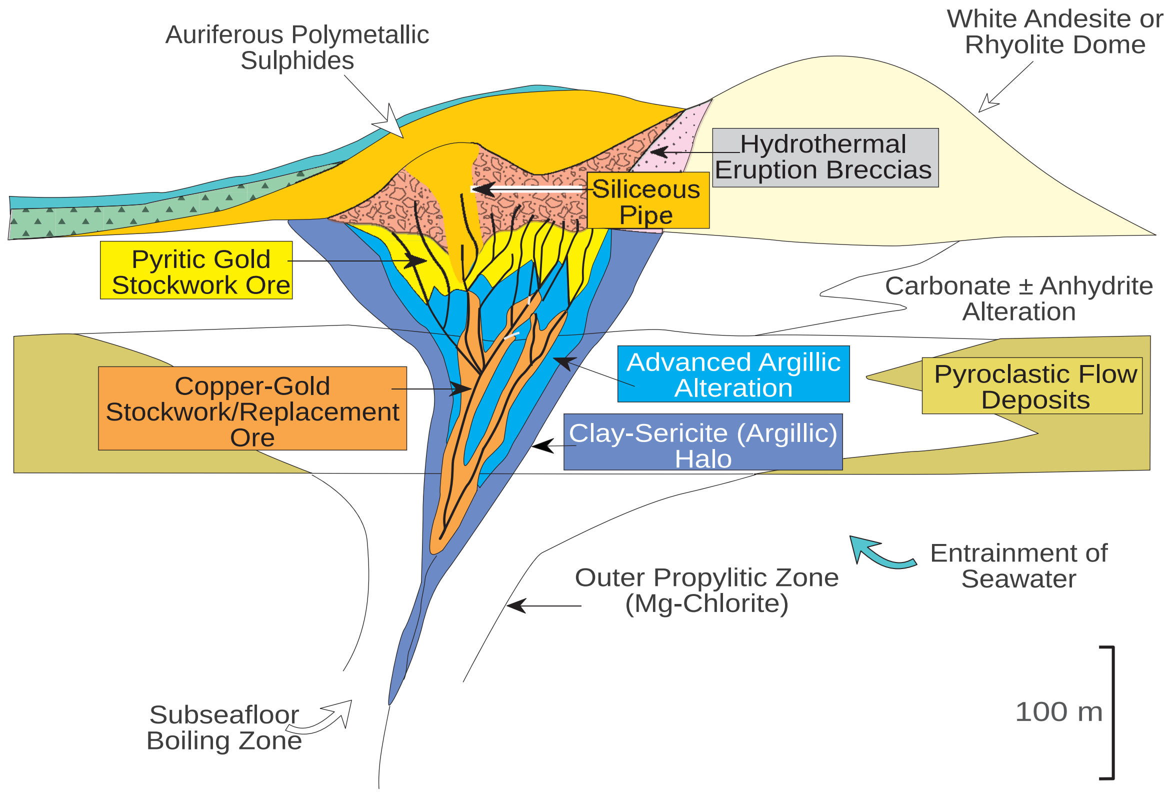

Figure 2. Schematic illustration of geological setting and hydrothermal alteration associated with Au-rich high-sulphidation volcanogenic massive sulphide hydrothermal systems (inspired by Hannington et al., 1999).

Gold-rich VMS deposits occur in both recent seafloor and in deformed and metamorphosed submarine volcanic settings within greenstone belts of various ages. In the latter, they may contain local syntectonic quartz-sulphide or, more rarely, quartz-tourmaline veins, which add to their complexity. They occur in a variety of submarine volcanic terranes, from mafic bimodal through felsic bimodal to bimodal siliciclastic. Their host strata are commonly underlain by coeval subvolcanic intrusions and sill-dyke complexes, and are typically metamorphosed to greenschist and lower amphibolite facies. The Au has most commonly an uneven distribution within the deposit due to both primary depositional controls and subsequent tectonic modification and remobilization. Some Au-rich VMS deposits are characterized by metamorphosed advanced argillic and massive silicic alteration indicative of an oxidized low-pH hydrothermal fluid that differs significantly from the mainly reduced, near neutral to weakly acidic fluids (of low-sulphidation conditions) typical of most ancient and modern VMS deposits (Sillitoe et al., 1996). Where present, the metamorphosed advanced argillic and massive silicic alteration assemblages are thought to indicate high-sulphidation conditions similar to those encountered in some epithermal environments (Fig. 2). In such cases, the Au-rich VMS deposits are commonly interpreted as shallow-water submarine equivalents to subaerial epithermal deposits (Hannington, 1993; Sillitoe et al., 1996; Hannington et al., 1999; Fig. 2).

Three types of Au-rich VMS deposits have been proposed based on common metallic associations (Huston and Large, 1989; Hannington et al., 1999): 1) an Au-Zn-Pb-Ag association in which Au is concentrated towards the top or along the margins of the massive sulphide lens; 2) an Au-Cu association where Au is concentrated at the base of the massive sulphide lens or within the underlying stringer zone; and 3) a pyritic Au group where Au is concentrated within massive pyrite zones with low base metals content.

Key characteristics of Au-rich VMS deposits and references are found in the text below.

Economic Characteristics of Gold-Rich Volcanogenic Massive Sulphide Deposits

Total world production and reserves of Au, including the Witwatersrand placer deposit, is 126,420 tonnes (t) (Gosselin and Dubé, 2005a). The Canadian production and reserves of Au stand at 9,280 t, representing 7% of the world total (Gosselin and Dubé, 2005a). Globally, Au-rich VMS deposit production and reserves account for 1370 t Au equivalent to 1% of the world production and reserves, whereas the Canadian total for Au-rich VMS is 870 t representing close to 10% of the Canadian production and reserves (Gosselin and Dubé, 2005a,b). The Blake River Group of the Abitibi subprovince, with 755 tonnes (t) of Au from Au-rich VMS, represents 13% of the known Au in the Abitibi greenstone belt and 85% of the production and reserves for that subtype of Au deposits in Canada. The Blake River Group, in particular within the Doyon-Bousquet-LaRonde district, is therefore an important geological assemblage for this type of Au deposit (Dubé et al., 2003).

Grade and Tonnage Characteristics

Au-rich VMS deposits range in size from small sulphide lenses with less than 3 t of Au, to giant-sized lenses and

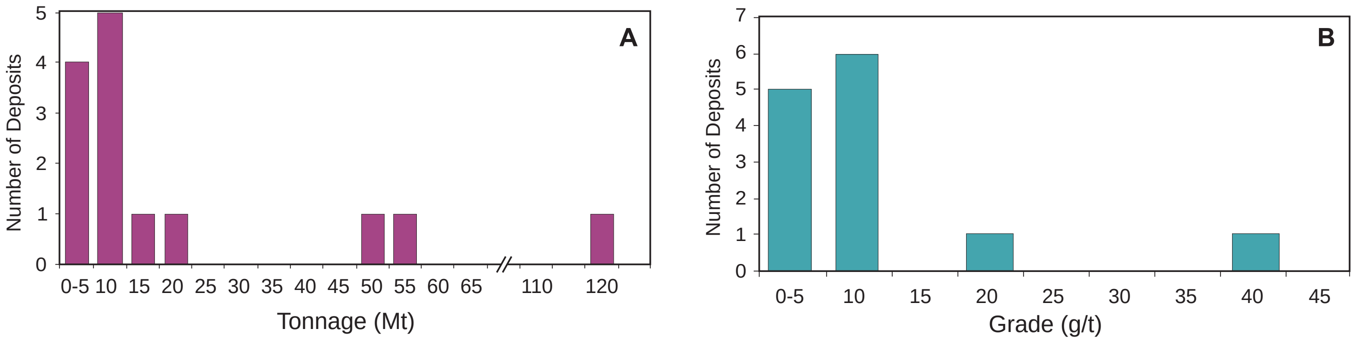

FIGURE 3. Histograms of tonnage **(A)** and grade **(B)** for Au-rich volcanogenic massive sulphide deposits worldwide (numbers include production, reserves and resources) (data from Gosselin and Dubé, 2005a).

stockwork-stringer zones of more than 50 million tonnes (Mt) of ore containing over 300 t of Au (Fig. 3A). Gold grade is typically greater than 4 g/t, with one deposit (Eskay Creek) reaching as high as 38 g/t (Figs. 3B, 4). Average Au grade for Canadian Au-rich VMS deposits is 5.9 g/t, however it may vary from 2.9 g/t up to 38 g/t. There are presently only eleven Au-rich VMS deposits in the world containing at least 30 t Au (approximately 1 Moz) in production, reserves, and resources (Fig. 5, Table 1). World-class deposits (≥100 t Au) form a select group of six deposits that includes the Paleoproterozoic Boliden deposit in Sweden (125 t Au produced) (Grip and Wirstam, 1970; Bergman-Weihed et al., 1996), one of the best known international examples, and Mount Morgan (Australia, 321 t Au in production, reserves, and resources). Some of the largest Au-rich VMS deposits are Canadian: Horne in the Noranda district (Cu-Au, 331 t of Au produced from 54.3 Mt of ore at 6.1 g/t Au, Kerr and Gibson, 1993), LaRonde Penna (Au-Zn-Ag-Cu) and Bousquet 2-Dumagami (Au-Ag-Cu-Zn, 112 t of Au produced) in the Doyon-Bousquet-LaRonde district, and Eskay Creek in British Columbia (Au-Ag-Cu-Zn-As-Sb-Hg, 81 t of Au produced and 37 t in reserves and resources). LaRonde Penna is the second largest Au-rich VMS deposit in Canada; it is also the largest Au deposit presently being mined in Canada. About 12.3 Mt of ore and 43.4 t of Au (1.4 Moz) have been extracted from the Penna shaft since the beginning of its production to the end of 2005 (Mercier-Langevin et al., 2007c). Reserves and resources at December 31, 2005 were evaluated at 6.74 Moz Au from 46.5 Mt at an average grade of 4.51 g/t Au, 2.04% Zn, 0.34% Cu, and 42.67 g/t Ag (Agnico-Eagle Mines, 2005 annual report).

Geological Setting of Gold-Rich Volcanogenic Massive Sulphide Deposits

Global-Scale Setting

Gold-rich VMS deposits occur in a variety of submarine volcanic terranes from mafic bimodal through felsic bimodal to bimodal siliciclastic in greenstone belts of all ages, typically metamorphosed to greenschist or lower amphibolite facies, and intruded by subvolcanic intrusions and dyke-sill complexes. The tectonic setting is commonly inferred to be island arcs, rifted arcs, back-arc basins, or back-arc rifts (Hannington et al., 1999; Huston, 2000). In modern volcanic settings, Au-rich VMS deposits are commonly associated with rifted-arc and incipient back-arc environments rather than mature back-arc spreading centres (Hannington et al., 1999). According to these authors, an association with rifted continental crust and continental margin arc environments may be particularly important for some districts (e.g. Boliden, Eskay Creek).

District-Scale Setting

Gold-rich VMS deposits coexist regionally with Au-poor VMS deposits, so that districts endowed with such deposits may well contain undiscovered Au-rich mineralization (Hannington et al., 1999). Their host strata are commonly underlain by coeval subvolcanic intrusions and sills or dykes. Consequently, large volumes of effusive rhyolite and associated felsic pyroclastic rocks (lithic tuffs, crystal tuffs, etc.) and the occurrence of subvolcanic intrusions or dyke swarms of tonalitic to granitic composition (Hannington et al., 1999) are important features of Au-rich VMS deposits. Apophyses developed on oxidized granitoids may be particularly important (Huston, 2000). Areas of transitional subaerial to shallow submarine volcanism are potentially very prospective (Hannington et al., 1999). Shallow-water volcanic complexes can be traced most readily through detailed mapping of volcanic and sedimentary facies (Hannington et al., 1999), and textures indicative of boiling, a process potentially responsible for the elevated Au content (see below), may also be a useful exploration guide (Huston, 2000).

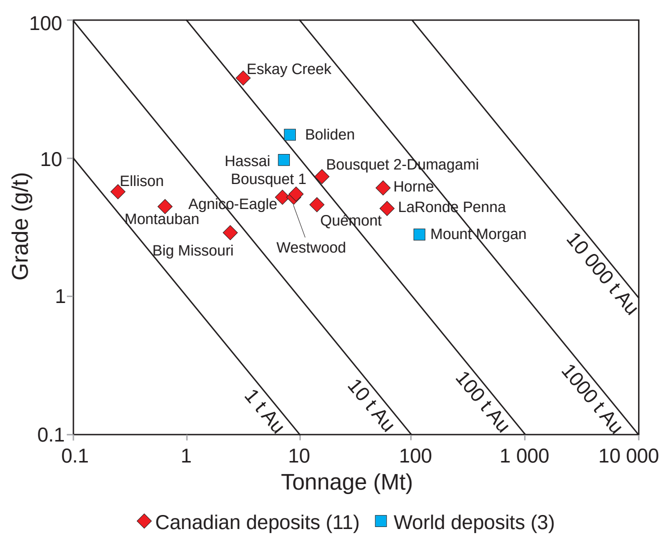

FIGURE 4. Tonnage versus grade of all Canadian Au-rich volcanogenic massive sulphide deposits and three international (>30 t Au) deposits (numbers include production, reserves, and resources) (data from Gosselin and Dubé, 2005a,b).

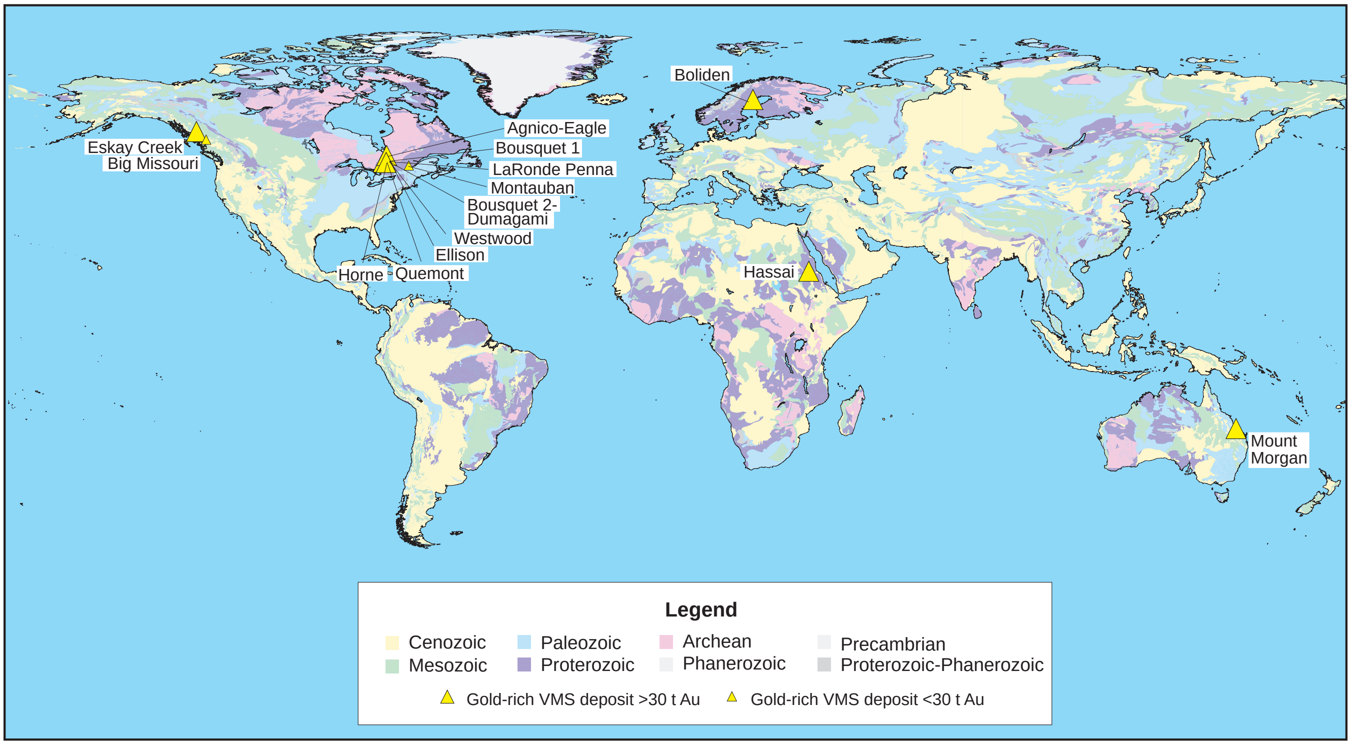

Figure 5. Map showing locations of Au-rich volcanogenic massive sulphide deposits.

Most deposits occur near synvolcanic fault-bounded blocks and horsts near extensional faults that commonly served as conduits for vent fluid. Post-volcanic deformation and metamorphism often caused remobilization of Au into faults and shear zones adjacent to the original sulphide lenses (Tourigny et al., 1993; Hannington et al., 1999). Pyritic quartz-sericite schists are a common host rock. Semiconformable zones of hydrothermal alteration are characterized by large aureoles of distal chloritic/propylitic (with sericite) alteration, surrounding more proximal zones of intense alteration near the deposit. These proximal zones may be characterized by sericitic to silicic/advanced argillic (aluminous) alteration indicative of low pH (acid) alteration (see below).

Base-metal enrichment and sodium-depletion anomalies may be important district-scale features (Huston, 2000). Barite commonly occurs near and within the younger deposits; barite-rich caps, barren pyrite lenses or exhalites are also found stratigraphically below or above deposits (Hannington et al., 1999).

The two largest Canadian Au deposits of this type (Horne and LaRonde Penna) are located a few kilometres from the Cadillac-Larder Lake fault, suggesting a possible empirical relationship with such large crustal faults.

Deposit-Scale Settings

The association of Au-rich VMS deposits with felsic volcanic rocks and tonalitic to granitic subvolcanic intrusions make these rock types important targets for exploration.

When deposits are chemically or mineralogically zoned, Au may have been leached from the base and centre of massive sulphide lenses and reprecipitated at the top due to gradual chemical refining of the ore (Ohmoto, 1996). Thus, variations in metal zonation, metal ratios, and ore thickness can be used to find the richest part of an orebody (Huston, 2000) even in deformed and metamorphosed terranes where these primary characteristics are commonly preserved despite

Table 1. Grade and tonnage of Au-rich volcanogenic massive sulphide deposits with at least 30 tonnes Au in production, reserves and resources.

Deposit Name	Country	Tonnage (Mt)	Au (g/t)	Ag (g/t)	Cu (%)	Zn (%)
Bousquet 1*	Canada	9.26	5.44			
Agnico Eagle**	Canada	6.93	5.18			
Dumagami*	Canada	15.48	7.25	5.54	0.52	0.03
Horne**	Canada	54.3	6.1	13	2.22	
LaRonde Penna*	Canada	58.76	4.31	44.96	0.33	2.17
Westwood*	Canada	8.61	5.19			
Quemont**	Canada	13.92	4.74	19.53	1.21	1.82
Eskay Creek**	Canada	3.12	37.99	1705.36		
Mt. Morgan**	Australia	116.04	2.77	0.51	0.5	
Hassai**	Sudan	7.18	9.74			
Boliden**	Sweden	8.3	15.09	48.31	1.42	

* Data from Mercier-Langevin et al. (2007).
** Data from Gosselin and Dubé (2005a).

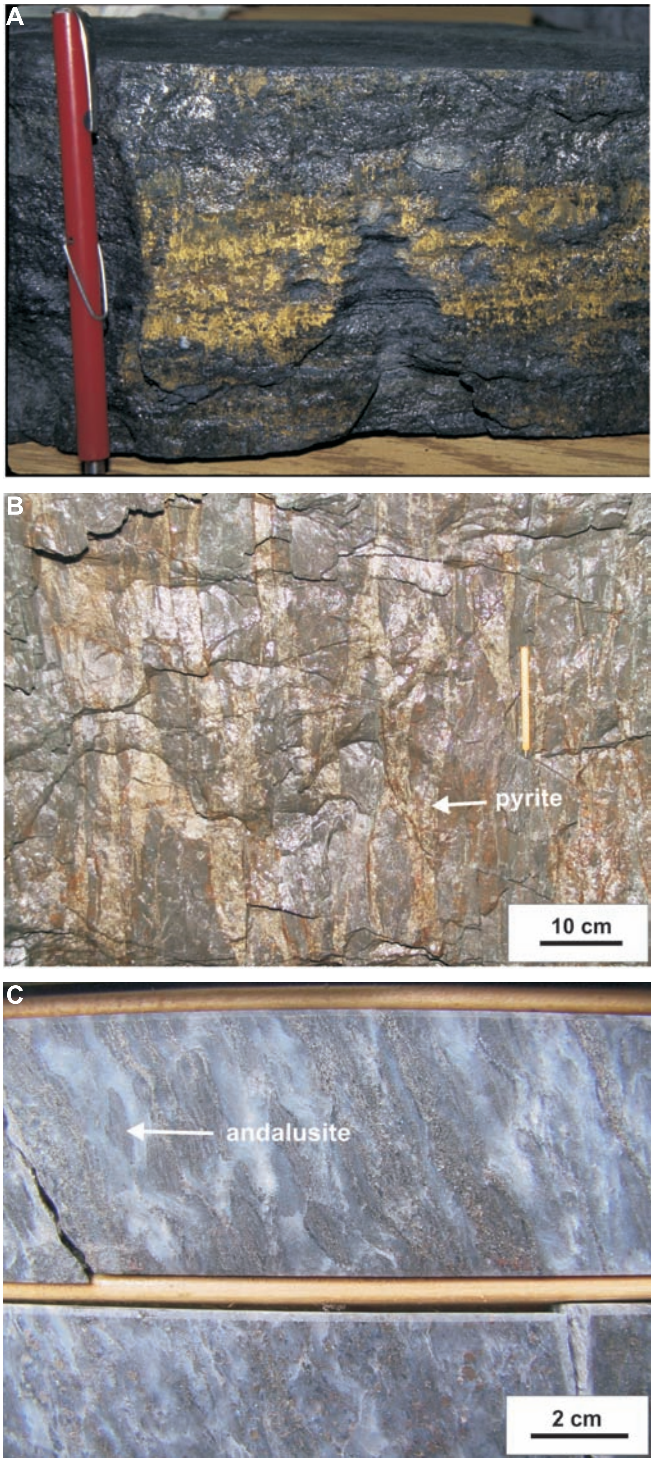

Figure 6. (A) Visible gold coating a late north-south-trending brittle fault plane, Dumagami mine. **(B)** Pyrite-rich stringer zone underneath lens 20 South, LaRonde Penna. **(C)** Quartz-andalusite-muscovite-pyrite schist, Bousquet 2 mine.

regional deformation and metamorphism (Mercier-Langevin, 2005).

Joints, faults, shears, and veins, either within or adjacent to sulphide lenses, may contain remobilized Au or Au reintroduced during deformation/metamorphism yielding attractive areas of high Au grades, as documented at the Bousquet 2-Dumagami deposit (Fig. 6A) (Marquis et al., 1990a; Tourigny et al., 1993).

Recognition of systematic mineralogical variations in alteration zones and distinctive proximal alteration assemblages, such as advanced argillic alteration and/or Mn-rich garnet-biotite assemblage, are important guides.

Possible geochemical anomalies are dependent on deposit Au-Cu versus Au-Zn-Pb-Ag associations. Deposits of the Au-Cu association show significant proximal depletion of Na and K, and enrichment of Cu, As, Mo, Bi, and Te, with distal enrichment of Zn, Ca, Mn, and C. Those of the Au-Zn-Pb-Ag association are characterized by an enrichment of As, Sb, and particularly Hg (Huston, 2000).

Geological Characteristics of Gold-Rich Volcanogenic Massive Sulphide Deposits

Physical Properties

Morphology

The typical morphology of Au-rich VMS deposits consists of a lenticular massive sulphide body with associated underlying discordant stockwork-stringer feeders and replacement zones (Fig. 6B). Some deposits, such as LaRonde Penna, contain stacked massive sulphide lenses (Fig. 7). The orebodies are commonly tabular and stratabound to discordant (e.g. LaRonde Penna 20 South lens). In most cases they have been deformed and tilted, and have a foliation-parallel pipe-like geometry due to their strong transposition along the main foliation and stretching lineation. In these cases, the stockwork-stringer zones may have been transformed to foliation-parallel sulphide veinlets in schistose, altered rocks with quartz, white mica, and sometimes aluminous silicates (Fig. 6C). At Horne, zones of auriferous sulphide veinlets with Fe-chlorite selvages account for some of the Au-rich ore (Kerr and Mason, 1990), however, the deposit lacks a well defined stringer zone (Poulsen et al., 2000). Early VMS mineralization at the Doyon deposit (Quebec) is overprinted by a large, telescoped epithermal or intrusion-related gold deposit associated with high-level emplacement of subvolcanic intrusions (Galley et al., 2003).

Dimensions

The vertical extent of the stockwork is typically larger than its lateral extension. In some cases where the deposits are overturned, the orebody has more than 2 km of known vertical extension (Horne and LaRonde Penna deposits). The lateral extension of the deposit is typically a few hundred metres. The thickness of the massive sulphide lenses is highly variable, especially when submitted to deformation (shortening), but commonly in the order of a few tens of metres.

Host Rocks

The mineralization is typically hosted by felsic volcanic flows and volcaniclastic rocks (or their metamorphosed equivalents) near or at the interface with basaltic andesite, andesite or clastic sedimentary strata (e.g. LaRonde Penna, Eskay Creek, and Boliden) (Fig. 8A,B).

The Horne deposit is contained within a fault-bounded block of tholeiitic rhyolite flows and pyroclastic breccias and tuffs in contact with andesite flows to the east (Fig. 9). It is

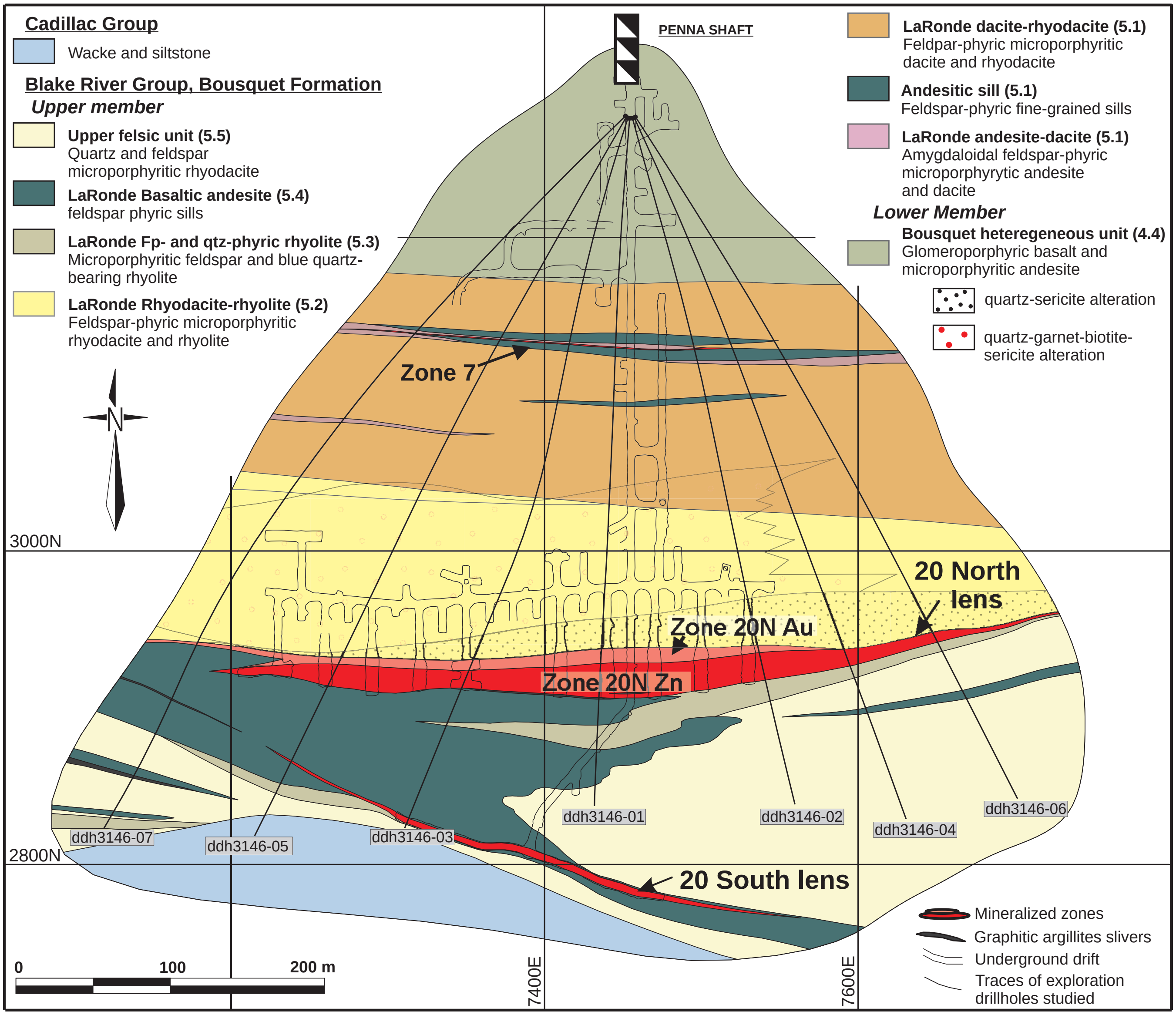

FIGURE 7. Geological plan of level 146 (1460 metres below surface) from drill core logging and drift mapping of the upper to middle portion of the LaRonde Penna deposit showing stratigraphy and sulphide lens stacking (modified from Dubé et al., 2004).

juxtaposed against andesite flows and a diorite intrusion to the south, and rhyolites to the north that contain the Quemont deposit, another auriferous massive sulphide deposit (Poulsen et al., 2000) potentially related to the same giant hydrothermal system responsible for the formation of the Horne deposit.

Textures

Banded and stratiform massive sulphide lenses and adjacent stockworks are commonly transposed by the main foliation in deformed deposits. In such cases, syntectonic sulphide veins may have developed, adding to the complexity and controversy of the deposits. Well preserved primary sulphide layering is rare to absent.

Mineralogy

The sulphide mineralogy of the Au-bearing ores is commonly more complex than in traditional Au-poor VMS deposits (Hannington et al., 1999). Sulphide minerals are mainly pyrite (Fig. 10), chalcopyrite, sphalerite, pyrrhotite, and galena with a complex assemblage of minor phases including locally significant amounts of bornite (Bousquet 2-Dumagami; Fig. 11A,B), tennantite, sulphosalts, arsenopyrite, mawsonite, and tellurides (Table 2). The strong association of tellurides with Au suggests a possible magmatic input in the hydrothermal fluid. The Boliden deposit contains nearly fifty different ore minerals (Ödman, 1941; Grip and Wirstam, 1970; Bergman Weihed et al., 1996), whereas more than twenty-five major and trace minerals have been identified in the ores at LaRonde Penna including arsenopyrite, tetrahedrite, tennantite, bornite, Pb-Sb and Ag-Sb sulphosalts, Cu-Sn-sulphides, native Bi, Bi-tellurides, Ag (-Au) tellurides, electrum and rare selenides (Fig. 12A,B; Dubé et al., 2004).

The Eskay Creek deposit is a low-temperature Au-rich VMS deposit characterized by a mineralogical assemblage of stibnite, realgar, cinnabar, and arsenopyrite with variable proportions of barite (Roth et al., 1999; Sherlock et al.,

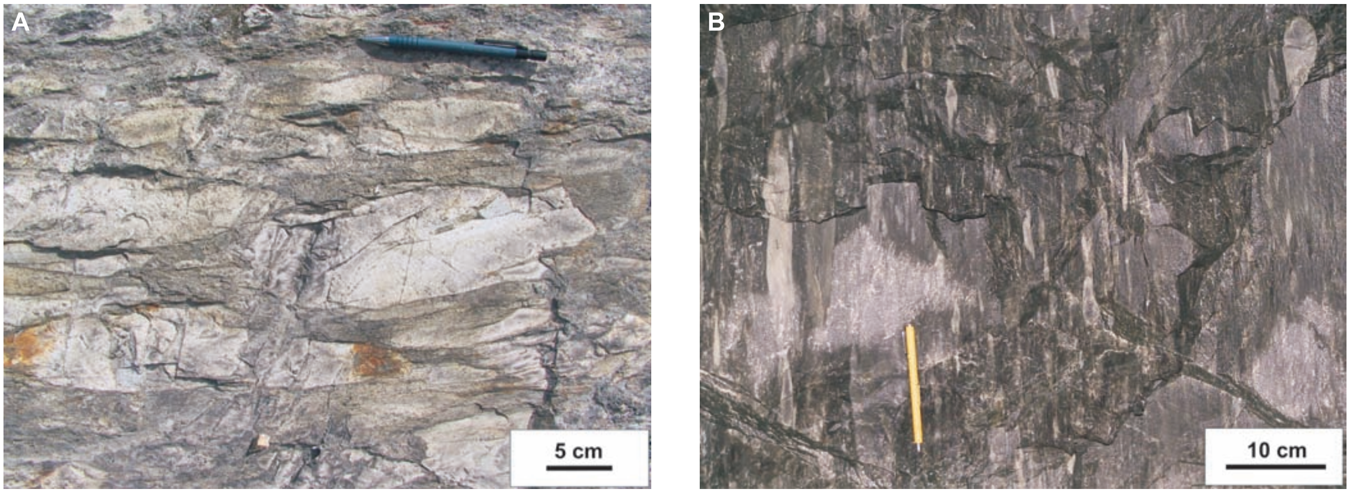

Figure 8. (A) Rhyodacitic talus breccia in the footwall of the 20 North massive sulphide lens, LaRonde Penna. **(B)** Rhyodacitic lapilli tuff (unit 5.5) in the footwall of the 20 South massive sulphide lens, upper member of the Bousquet Formation, LaRonde Penna.

1999). The 21A zone consists of stratabound to stratiform lenses of semimassive to massive stibnite and realgar, whereas the 21B zone is a stratiform sulphide-sulphosalt Zn-Pb-Au-Ag zone. The sedimentary textures of the stratiform 21B zone are consistent with its detrital origin (Fig. 13A,B) (Poulsen et al., 2000); it is thus clearly distinct from other Au-rich VMS deposits.

As indicated by Hannington et al. (1999), Au occurs mainly as native metal and Au-tellurides in Cu-Au VMS deposits, whereas auriferous, polymetallic (Au-Zn-Pb-Ag) VMS typically contain electrum, which is often Ag- or Hg-rich (cf. Huston et al., 1992). In some deposits, Au is mainly hosted in commonly refractory arsenic-rich pyrite and arsenopyrite and present as submicroscopic inclusions or structurally bound to the crystal lattice (Huston et al., 1992; Larocque et al., 1993, and references therein). In metamorphosed deposits such as LaRonde Penna, metamorphic remobilization and segregation has had an impact on the local distribution of Au in the ores and has played an important role in generating non-refractory Au minerals (Dubé et

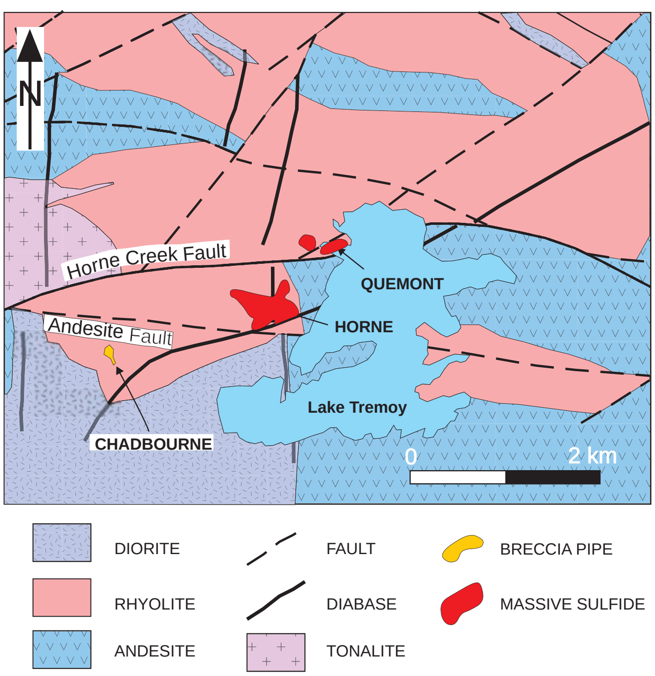

Figure 9. Simplified map of the geology around the Horne deposit, Rouyn-Noranda district, modified from Cattalani et al. (1993); massive sulphide deposits are projected to surface (from Poulsen et al., 2000).

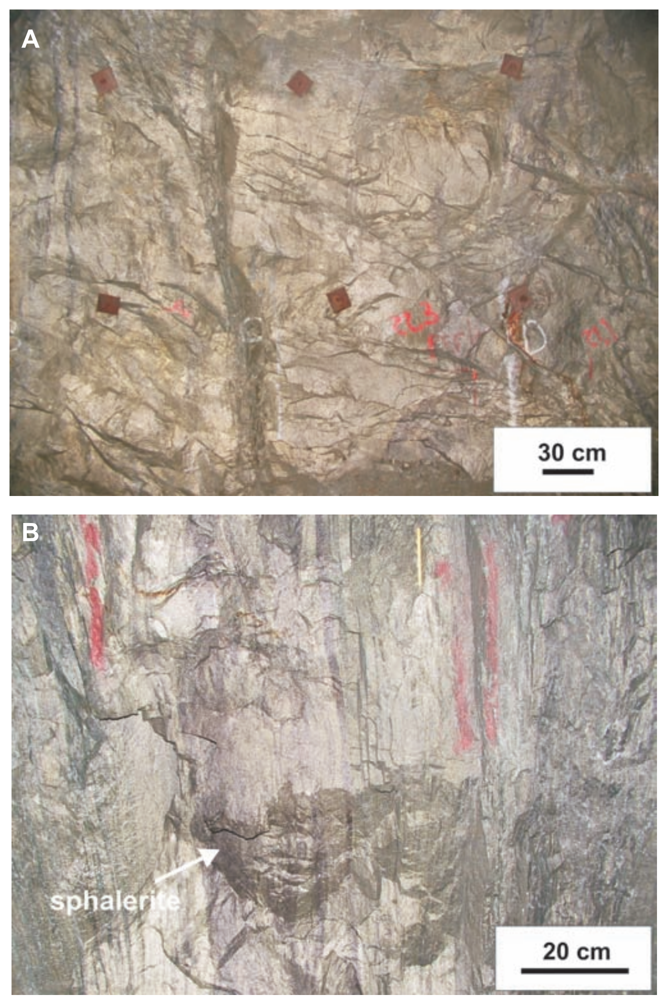

Figure 10. (A) Massive pyrite zone, lens 20 North, LaRonde Penna. **(B)** Massive pyrite with layers of sphalerite, lens 20 South, grading 34 g/t Au and 8% Zn over 10 metres, LaRonde Penna.

Table 2. Mineralogy of the LaRonde and selected Au-VMS deposits in the Doyon-Bousquet-LaRonde district (from Dubé et al., 2004).

	LaRonde[2]		Bousquet 2		Dumagami		Bousquet 1	
Major Minerals	Pyite	FeS_2	Pyite	FeS_2	Pyite	FeS_2	Pyite	FeS_2
	Pyrrhotite	$Fe_{1-x}S$	Chalcopyite	$CuFeS_2$	Chalcopyite	$CuFeS_2$	Chalcopyite	$CuFeS_2$
	Chalcopyite	$CuFeS_2$	Bornite	Cu_5FeS_4	Sphalerite	ZnS		
	Sphalerite	ZnS						
	Galena	PbS						
Minor Minerals	Arsenopyrite	FeAsS	Sphalerite	ZnS	Galena	PbS	Sphalerite	ZnS
	Tetrahedrite	(Ag) $Cu_{12}(Sb,Ag)_4S_{13}$	Galena	PbS	Arsenopyrite	FeAsS	Pyrrhotite	$Fe_{1-x}S$
	Stannite	Cu_2FeSnS_4	Tennantite	(Te)$(Cu,Zn,Fe)_{13}(As,Sb,Te)_4S_{12}$	Bornite	Cu_5FeS_4	Magnetite	$FeFe_2O_4$
	Magnetite	$FeFe_2O_4$	Chalcocite	Cu_2S	Chalcocite	Cu_2S	Arsenopyrite	FeAsS
			Pyrrhotite	$Fe_{1-x}S$	Covellite	CuS	Galena	PbS
			Magnetite	$FeFe_2O_4$	Digenite	Cu_9S_5	Bornite	Cu_5FeS_4
Trace Minerals	Electrum	AuAg	Electrum	AuAg	Electrum	AuAg	Electrum	AuAg
	Hessite	Ag_2Te	Hessite	Ag_2Te	Altaite	PbTe	Au-Telluride	Ag_3AuTe_2; $AuTe_2$
	Native Bi		Petzite	Ag_3AuTe_2	Cu-Ag-sulphide		Altaite	PbTe
	Bi-telluride[3]		Altaite	PbTe	Stannite	Cu_2FeSnS_4	Stannite	Cu_2FeSnS_4
	Ag-Bi sulphide Mathildite	$AgBiS_2$	Tellurobismuthite	Bi_2Te_3	Alabandite	MnS	Gudmundite	FeSbS
	Cu-Pb-Bi-sulphide[4]		Mawsonite	$Cu_6Fe_2SnS_8$				
	Pb-Sb sulphosalts[5]		Colusite	$Cu_{26}V_2(As,Sn,Zn,Ge)_6S_{32}$				
	Ag-Sb sulphosalts[6]		Renierite	Cu_3GeFeS_4				
	Gudmundite	FeSbS						
	Clausthalite	PbSe						
	Colusite	$Cu_{26}V_2(As,Sn,Zn,Ge)_6S_{32}$						
	Scheelite	$CaWO_4$						
	Cassiterite	SnO_2						

[1]LaRonde: Dubé et al. (2004); Bousquet 2: Tourigny et al. (1993); Dumagami: Marquis et al. (1990a); Bousquet 1: Tourigny et al. (1992).

[2]All ore zones, excluding Zone 5

[3]Bi-telluride = joseite-like compositions Bi_4Te_2S;

[4]Cu-Pb-Bi-sulphide = wittichenite; Cu_3BiS_3 and unidentified Mn-Bi-Pb-Sb sulphosalt;

[5]Pb-Sb sulphosalts = boulangerite $Pb_5Sb_4S_{11}$ and bournonite $PbCuSbS_3$;

[6]Ag-Sb sulphosalts = dyscrasite Ag_3Sb.

al., 2004). At LaRonde Penna, free Au (as electrum) accounts for the majority (>90%) of the Au in the ore (Dubé et al., 2004). The Au grains are typically very fine (1-5 microns) and occur mainly as inclusions in recrystallized pyrite and chalcopyrite, and within microfractures in recrystallized pyrite. The electrum typically occurs intimately intergrown with other remobilized trace minerals (Fig. 12B).

Chemical Properties

Ore Chemistry

The chemical signature of the ore is dominated by Au, Ag, and Cu or Zn with locally high concentrations of As, Sb, Bi, Pb, Se, Te, and Hg. At Eskay Creek, elevated Sb, As, Hg, and Ba are characteristic of the high-grade ore (Roth et al., 1999). Where associated with Cu, Au is commonly concentrated within the stockwork-stringer zone in the immediate footwall of the massive sulphide lens (e.g. LaRonde Penna, 20 North Au lens below the 20 North Zn massive sulphide lens, Dubé et al., 2004) (Huston, 2000). Where associated with Zn, Au is located toward the upper part (Huston, 2000) or throughout the massive sulphide lens (e.g. 20 South lens at LaRonde Penna, Dubé et al., 2004; Fig 10B). Silver is commonly more abundant than Au and the Ag/Au ratios typically vary from 1:2 to 10:1.

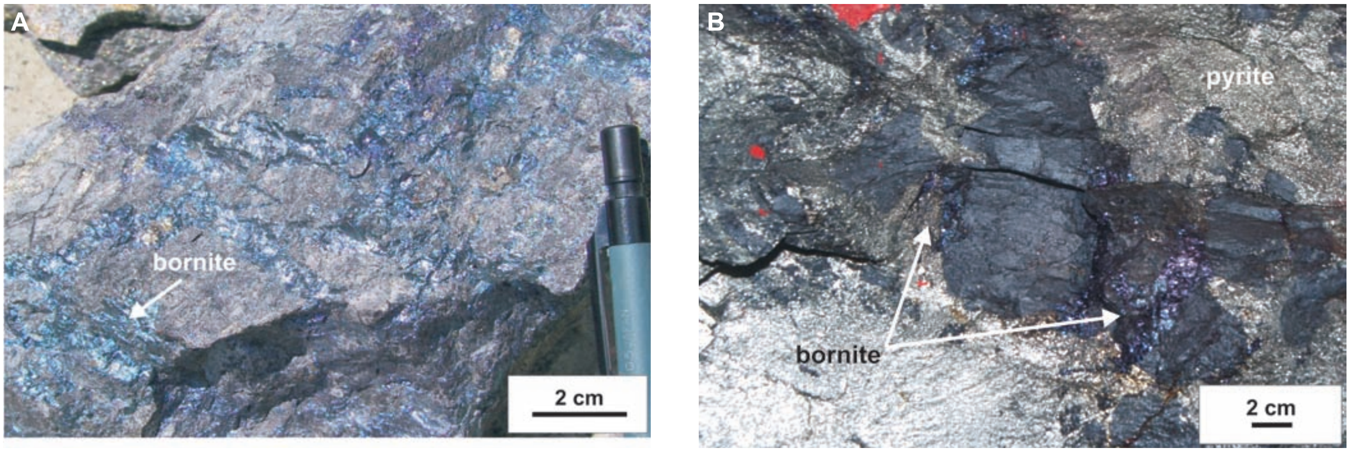

Figure 11. (A) Bornite veins cutting across highly silicified dacite (Bousquet 2 mine). **(B)** Bornite veinlets cutting highly silicified clast within massive pyrite lens (Bousquet 2 mine).

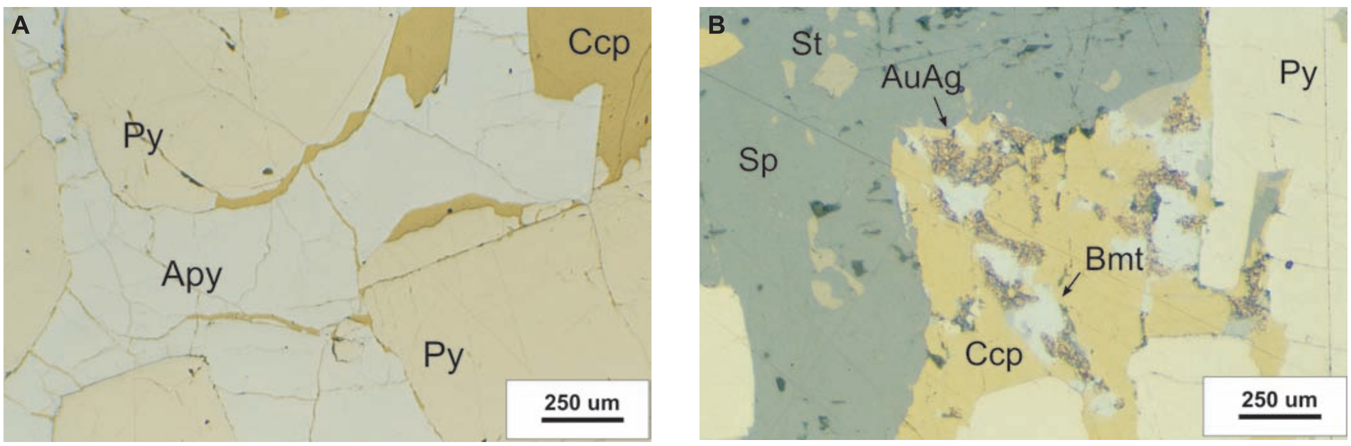

Figure 12. Photomicrographs showing typical ore textures and mineral assemblages of the different ore zones in the LaRonde mine (Apy: arsenopyrite; AuAg: electrum; Bmt: bismuthinite; Ccy: chalcopyrite; Py: pyrite; Sp: sphalerite; St: stannite (from Dubé et al., 2004).

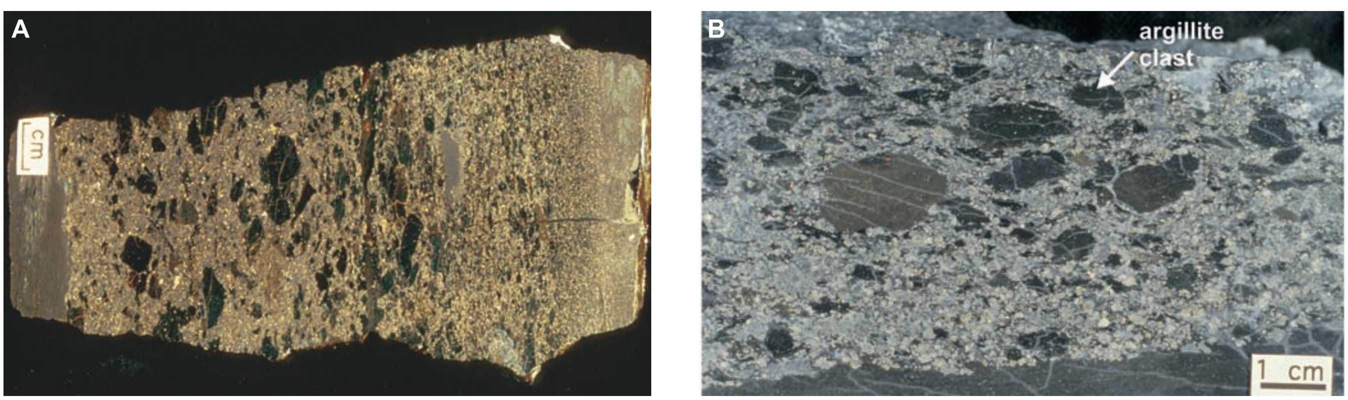

Figure 13. (A) Graded sulphide-silicate turbidite bed. **(B)** Tetrahedrite-rich (light grey) sedimentary debris flow containing siliceous argillite clasts (dark grey to black). Both photographs from the 21B zone, Eskay Creek (from Poulsen et al., 2000).

Alteration Mineralogy

In the Doyon-Bousquet-LaRonde district, the alteration assemblages proximal to or hosting the ore are commonly characterized by semiconformable to discordant zones of metamorphosed advanced argillic (aluminous) alteration with quartz, sericite, andalusite and/or kyanite, pyrophyllite and by local Zn-rich staurolite (Figs. 14A-D, 15A) and massive silicic alteration with strong to complete leaching of Na_2O, CaO, MgO, and K_2O (Fig. 15A,C; Valliant and Barnett, 1982; Dubé et al., 2004, in press). SiO_2, Al_2O_3, and TiO_2 have commonly been affected by residual enrichment due to the removal of the other oxides, although SiO_2 could have also been added through silicification. The advanced argillic alteration Index (AAAI=100 (SiO_2/(SiO_2+10MgO+10CaO+10Na_2O)) has been proposed recently to quantify such intense acid leaching with SiO_2 enrichment and to help in mapping the various alteration zones (Williams and Davidson, 2004). Andalusite and/or kyanite are commonly

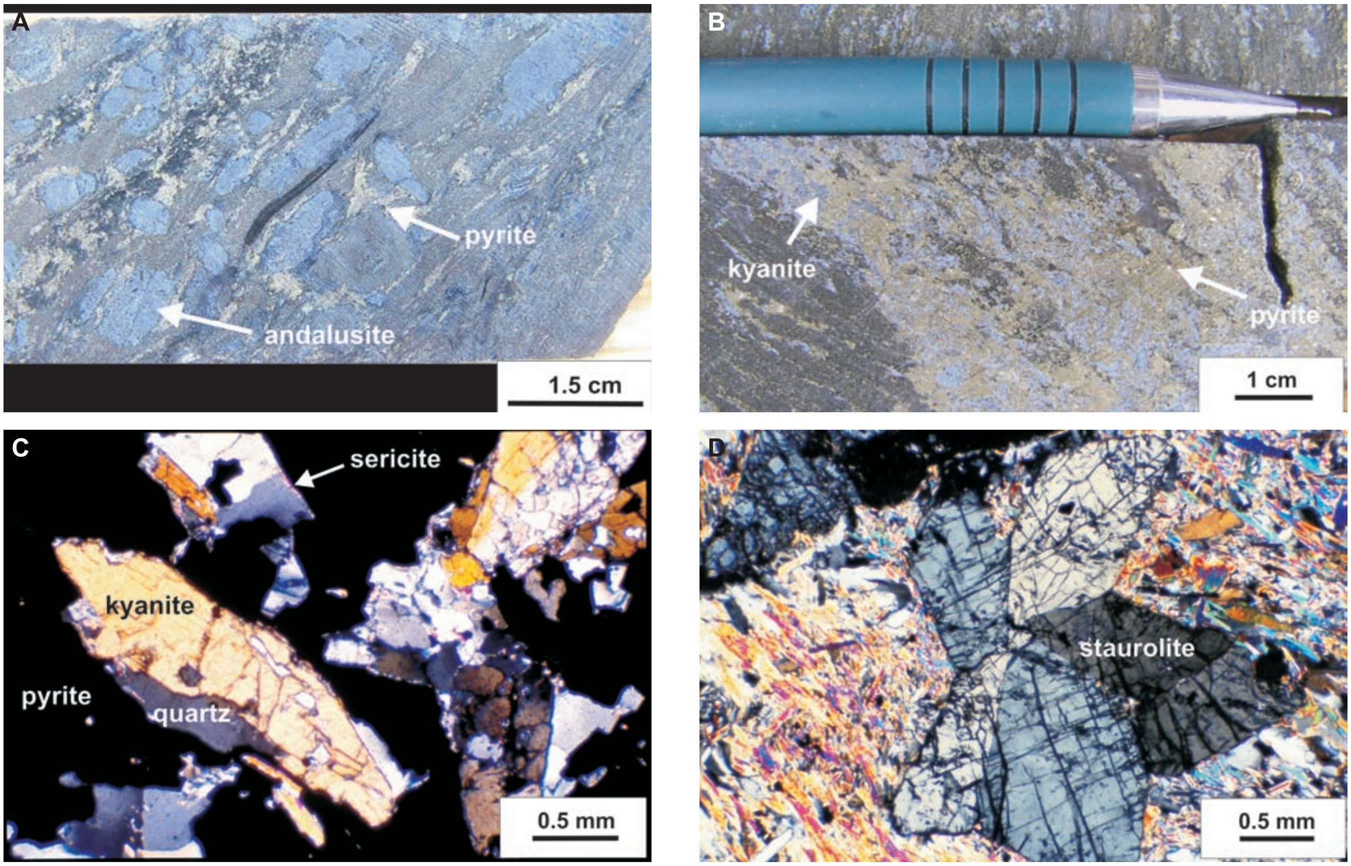

FIGURE 14. **(A)** Andalusite, kyanite, and pyrite replacement and stockwork ore zone, LaRonde Penna. **(B)** Kyanite and pyrite-rich replacement-style ore zone, LaRonde Penna. **(C)** Kyanite crystals (yellow, brown) in pyrite (black) and quartz (white, grey), LaRonde Penna (polarized light). **(D)** Zn-rich staurolite (blue, grey, and beige) in sericitic matrix, LaRonde Penna (polarized light).

retrograded into pyrophyllite (e.g. LaRonde Penna, Bousquet 2-Dumagami) (Marquis et al., 1990c; Tourigny et al., 1993; Dubé et al., 2004, in press).A proximal quartz-biotite-Mn-rich garnet assemblage or an outer quartz-manganiferous garnet-Zn-rich staurolite-chloritoid-biotite-muscovite-chlorite assemblage may be present, especially in the footwall of the mineralization (Fig. 15B; Valliant and Barnett, 1982, Dubé et al., 2004). Green chromium mica may also be locally present, as illustrated by the presence of chromium-rich phengite in both the immediate footwall and hanging wall of the 20 South lens at LaRonde Penna (Dubé et al., 2004, in press; Fig. 15D) and in the footwall of the Rambler deposit in Newfoundland. The North and South ore zones at Montauban are associated with disseminated pyrite, sphalerite, and chalcopyrite, with cordierite-anthophyllite and quartz-biotite garnet assemblages within quartz-biotite and quartz-sillimanite gneisses (Morin, 1987). Potassic alteration, characterized by K-feldspar, occurs at Eskay Creek, especially in the footwall alteration zone (Roth et al., 1999). Huston (2000) proposed that the advanced argillic alteration is more typical of the Au-Cu subclass of Au-rich VMS deposits, whereas potassic feldspar is more common of those characterized by the Au-Zn-Pb-Ag association. Tourmaline is present at Boliden as lens-shaped auriferous tourmaline ore located beneath the massive sulphide zone within the sericitic alteration, as well as minor high-grade quartz-tourmaline veins (Bergman Weihed et al., 1996). Traces to minor amounts of tourmaline are also present at LaRonde Penna (Dubé et al., in press).

At the Horne deposit, most rhyolitic rocks within the fault-bounded block have been affected by weak sericitization and silicification that become more intense near the orebodies, where alteration is characterized by a quartz-sericite±pyrite assemblage (Poulsen et al., 2000). Chlorite alteration, which locally contains elevated Cu and Au values, is largely restricted to the immediate footwall and sidewall of the deposit, except for local discordant zones in the footwall (Barrett et al., 1991).

Distribution of Canadian Gold-Rich Volcanogenic Massive Sulphide Districts

Due to the low number of Au-rich VMS deposits, there are relatively few districts containing Au-rich VMS deposits in Canada and around the world. Districts listed in Table 3 contain Au-rich VMS deposits as well as other Au-poor VMS, epithermal, intrusion-related (Au-Cu sulphide-rich veins), or greenstone-hosted quartz-carbonate vein deposits. However, production, reserves, and resources figures listed are for deposits of the Au-rich VMS subtype only.

Gold-rich VMS deposits are distributed in areas where hydrothermal activity took place in tectonically active, arc- or back-arc-related seafloor environments representing volcanic terranes located in orogenic belts and greenstone belts, frequently near major crustal-scale faults and large subvol-

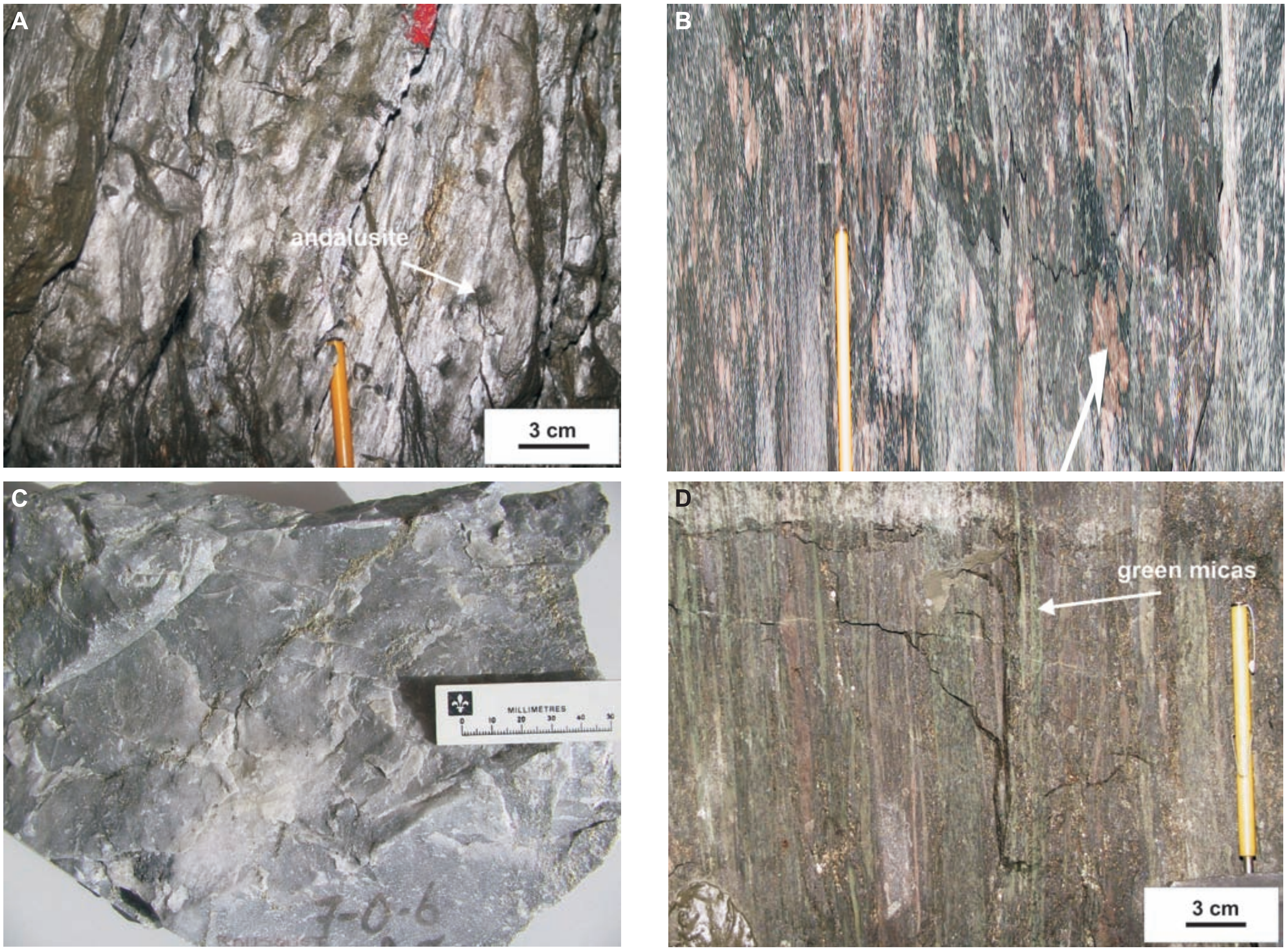

Figure 15. **(A)** Quartz-muscovite-andalusite schist in the footwall of the 20 North lens, LaRonde Penna. **(B)** Deformed Mn-rich garnet-biotite alteration zone at the base of the 20 North lens, LaRonde Penna. **(C)** Massive silicic alteration (97% SiO_2) cut by pyrite stringers at the base of the massive sulphide lens, Bousquet 2 mine. **(D)** Banded green mica alteration hosting the 20 South lens, LaRonde Penna.

canic intrusions. In Canada, such settings are found in Archean greenstone belts within the Superior Province (Rouyn-Noranda and Doyon-Bousquet-LaRonde districts), in the Paleozoic Dunnage zone of the Appalachians (e.g. Baie Verte district), and the Mesozoic Intermontane Belt of the Canadian Cordillera (Iskut River district). High metamorphic grade, Proterozoic volcanic rocks hosting the Montauban deposit (Montauban district), Grenville Province, are thought to be related to island-arc or back-arc environments (MacLean et al., 1982; Nadeau et al., 1999).

Canadian Au-rich VMS deposits with a total Au content of at least 30 t Au are located mainly in the Abitibi greenstone belt and are Late Archean in age (Fig. 16). Figure 16 also shows that the total Au content of the Canadian Archean Au-VMS deposits is larger than anywhere else. They have an average grade of 5.35 g/t Au and their tonnage ranges from 6.93 Mt (Agnico-Eagle Telbel) to more than 58 Mt (LaRonde Penna). The Horne and Quemont deposits are located in the Rouyn-Noranda district (see Fig. 17 for location of districts). This district also contains a large number of greenstone-hosted quartz-carbonate vein and VMS deposits that are not sufficiently enriched in Au to fall into the Au-rich VMS category.

The Doyon-Bousquet-LaRonde district hosts three producing mines (LaRonde Penna, Doyon, and and Mouska) and several past producers (Bousquet 1, Bousquet 2-Dumagami, Mooshla A and B, and MicMac), as well as two significant undeveloped deposits (Westwood and Ellison, Fig. 18; Mercier-Langevin et al., 2007c). It is the second largest Au camp in Quebec and one of the most prolific Archean Au-rich VMS districts with more than 462 t Au (past production, reserves, and resources). The LaRonde Penna deposit represents one of the largest complexes of Au-rich VMS lenses in the world. The VMS deposits in the camp are hosted by the upper portion of the Blake River Group

Table 3. List of Canadian Au-rich volcanogenic massive sulphide districts.

District	Geological Province	Production (tonnes Au)	Resources +Reserves*
Doyon-Bousquet-LaRonde	Superior/Abitibi	195	267
Rouyn-Noranda	Superior/Abitibi	397	
Joutel	Superior/Abitibi	36	
Iskut River	Cordilleran	83	43
Montauban	Grenville	3	

*(tonnes Au)

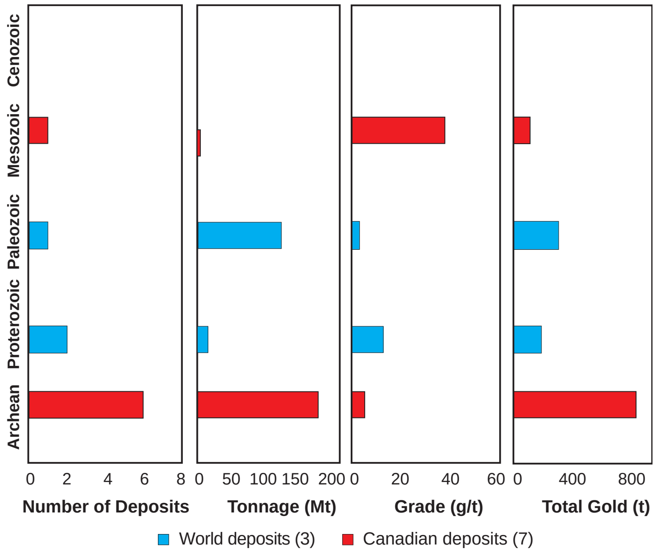

FIGURE 16. Comparison of Au-rich volcanogenic massive sulphide deposits (≥30 t Au) from different geological periods (data from Gosselin and Dubé, 2005a,b).

(Bousquet Formation), which also hosts most of the VMS deposits located in the nearby world-class Noranda district. The Doyon mine is the second largest deposit in the district with 206 t of Au in production, reserves, and resources. Early VMS mineralization at Doyon is overprinted by a telescoped sulphide-rich epithermal or intrusion-related, pre-to early deformation vein-type deposit associated with high-level emplacement of subvolcanic intrusions (Galley and Lafrance, in press). The only other operating mine in this district is the greenstone-hosted quartz-carbonate vein Mouska deposit (Belkabir and Hubert, 1995).

The Joutel district contains the Agnico-Eagle (Telbel) Au-rich VMS deposit, where disseminated to semimassive sulphide lenses and stringers are hosted by carbonate-altered volcanogenic sedimentary rocks and felsic tuffs. The origin of the deposit has been the subject of debate between syngenetic exhalative (Barnett et al., 1982; Dubé et al., 1991) and syndeformation epigenetic (Wyman et al., 1986), but colloform textures, breccias, and a ribboned sulphide facies have led Gauthier et al. (2000) to infer a shallow-water setting close to the Mattabi style of VMS deposits. Two Cu-Zn VMS deposits exploited in the early 1960s (the Joutel Copper and Poirier mines) occur less than 5 km from the Agnico-Eagle deposit, and within the area are also other VMS deposits (such as the Selbaie Cu-Zn-Au-Ag deposit) and greenstone-hosted quartz-carbonate veins Au deposits (e.g. Casa-Berardi).

The only Canadian deposit of Proterozoic age is the Montauban deposit (Grenville Province, Quebec), which has produced some 2.8 t Au from ore grading 4.5 g/t. There is no other known Au deposit in the Montauban area. Proterozoic examples outside Canada include Boliden (Sweden) and Hassai (Sudan). Boliden is a controversial Paleoproterozoic deposit located within the upper part of 1.89 to 1.87 Ga dacite-rhyodacite calc-alkaline volcanic rocks near the interface with a sedimentary sequence (Bergman Weihed et al., 1996). The deposit is characterized by predeformation massive pyrite±arsenopyrite ore, overprinted by less abundant auriferous quartz-chalcopyrite-sulphosalt and quartz-tourmaline veins, with associated andalusite-sericite-quartz

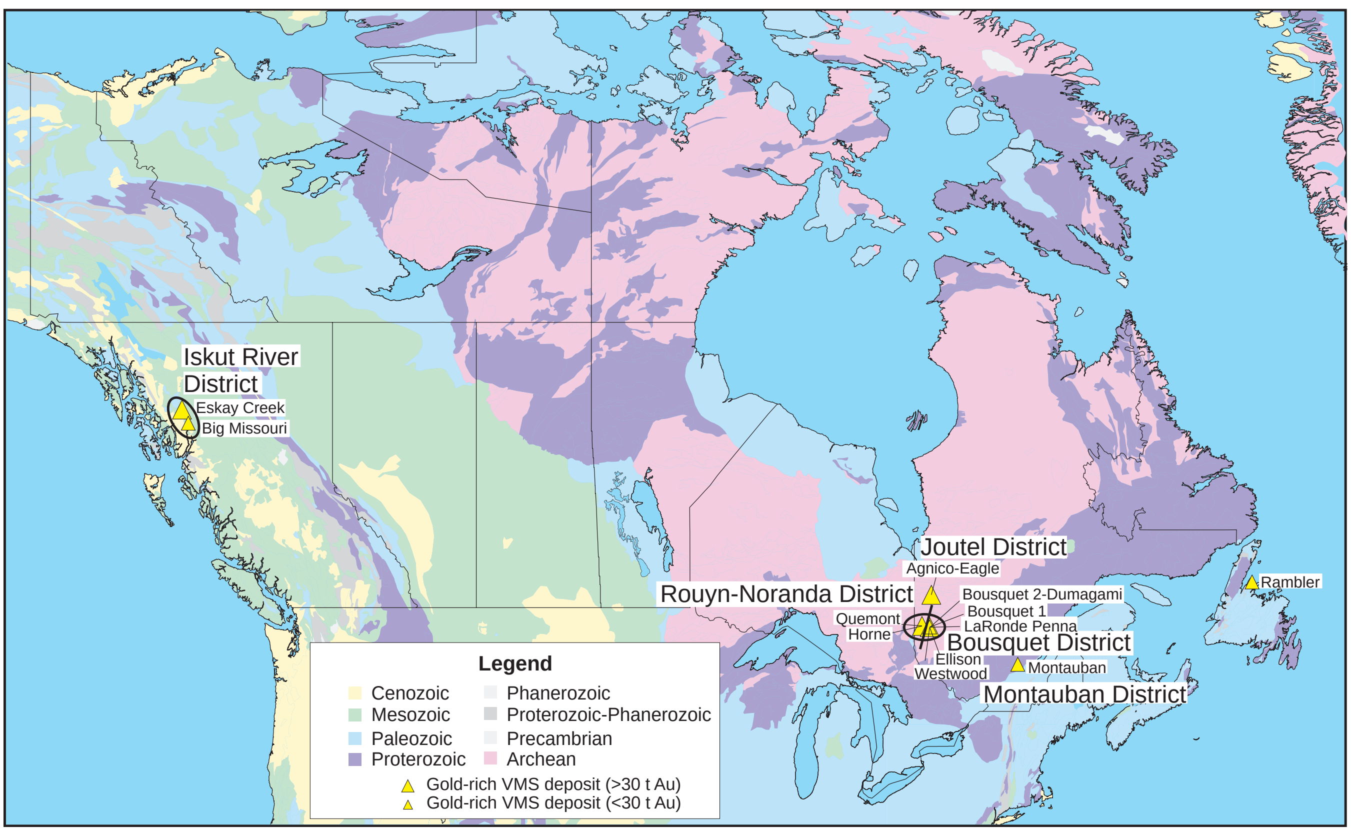

FIGURE 17. Locations of Au-rich volcanogenic massive sulphide districts in Canada.

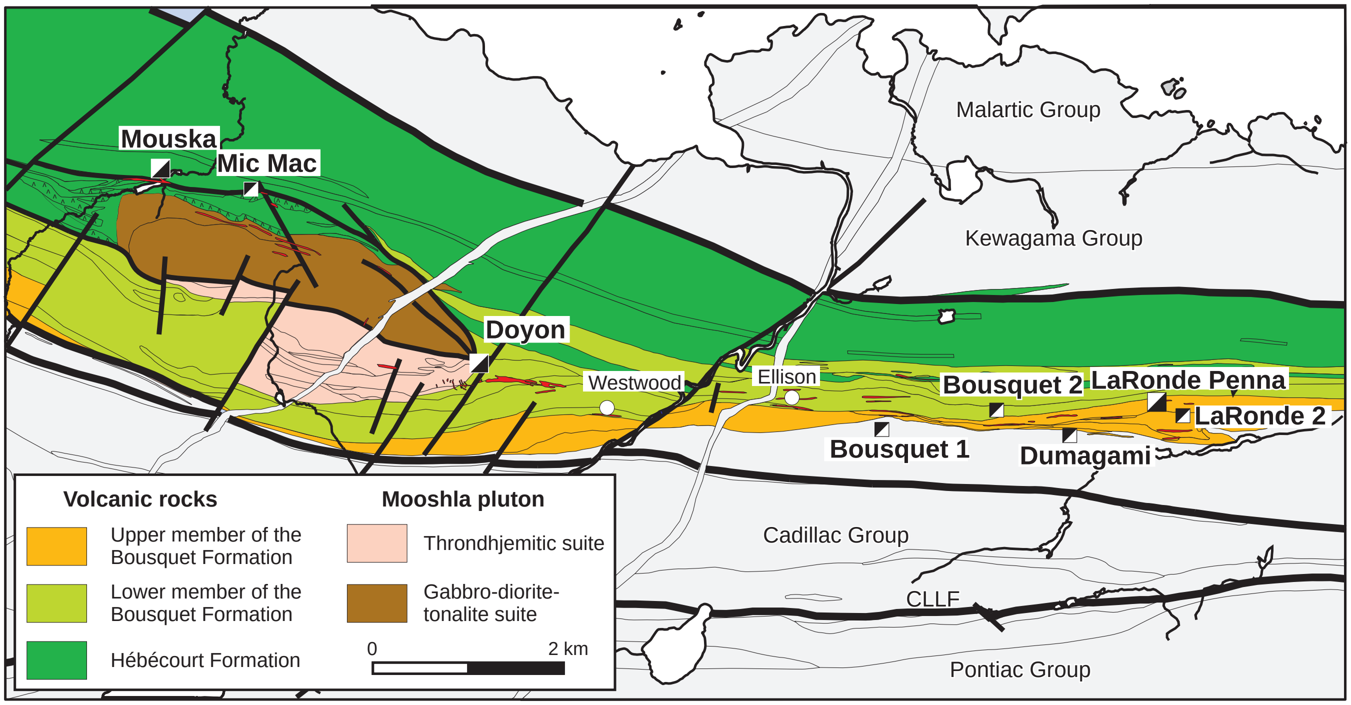

FIGURE 18. Simplified geological map of the Doyon-Bousquet-LaRonde district showing the main geological features and mine locations (from Dubé et al., 2003). CLLF = Cadillac-Larder Lake Fault.

assemblages (Nilsson, 1968; Bergman Weihed et al., 1996). The deposit has been interpreted as a replacement metamorphic deposit (Ödman, 1941), a synvolcanic exhalative deposit (Rickard, 1986), a subseafloor replacement deposit (Allen et al., 1996), a high-sulphidation epithermal deposit (Bergman Weihed et al, 1996), and a subseafloor replacement deposit transitional between a VMS and a high-sulphidation deposit (Doyle and Allen, 2003).

A small Paleozoic deposit, the Rambler Cu-Zn-Au-Ag deposit in Newfoundland (6.9 t Au from ore grading 1.54 g/t), is located in a greenstone belt of the Dunnage zone (Appalachians) (Hibbard, 1983; Coates, 1990). Although not a gold-rich VMS due to average Cu grades exceeding Au grades, the Rambler Main mine (399,093 t at 1.3% Cu, 2.16% Zn, 5.14 g/t Au, and 29.14 g/t Ag, Coates, 1990) was a small but significantly gold-rich portion of the deposit. Rambler occurs along the flank of a felsic dome and is hosted by felsic volcaniclastic rocks (dacitic tuffs, lapilli tuffs, and agglomerates) overlain by mafic to intermediate flows and volcaniclastic rocks (Coates, 1990). Similarly to the LaRonde Penna deposit, a portion of the footwall of the Main mine orebody at Rambler is characterized by Au-rich quartz-sericite-green mica schists with up to 4.8 g/t Au. The Baie Verte district has a number of other deposits of the greenstone-hosted quartz-carbonate vein subtype as well (e.g. Stog'er Tight, 3.4 t Au). The largest Paleozoic deposit is Mount Morgan (116 Mt at 2.77 g/t Au for 321 t of Au, (Gosselin and Dubé, 2005a) in Australia.

The Intermontane belt of the Canadian Cordillera hosts the Mesozoic Iskut River district with two deposits: one is the world-class, high-grade Eskay Creek deposit (3.1 Mt of ore at 38 g/t Au, Gosselin and Dubé, 2005b); the other is the smaller Big Missouri deposit (2.5 Mt of ore at 2.9 g/t Au) (British Columbia MINFILE database #104B 046). Other significant deposits of this district are Au-Cu sulphide-rich veins (Snip deposit, 32 t Au) (British Columbia MINFILE database #104B 250) and (mainly) low-sulphidation epithermal deposits (Silbak Premier, 65 t Au) (Gosselin and Dubé, 2005b). The Eskay Creek deposit is hosted by Lower Jurassic rocks of the Hazelton Group in the Stikine Terrane in a stratigraphic sequence consisting of felsic flow-banded volcanic rocks and breccias of a flow dome complex overlain by marine argillites and pillow basalts (MacDonald et al., 1996). The deposit consists of stratabound to stratiform lenses of semimassive to massive stibnite and realgar (21A Zone) and a stratiform sulphide-sulphosalt Zn-Pb-Au-Ag zone composed of stibnite, arsenopyrite, pyrite, sphalerite, galena, and tetrahedrite (21B Zone) (Poulsen et al., 2000). The sedimentary textures of the stratiform ore in the 21B Zone are consistent with a debris flow, whereas the 21A Zone, with its underlying stockwork and disseminated ore zones, shares some analogies with epithermal mineralization (Poulsen et al., 2000). Alteration of the underlying volcanic rocks includes chloritization, silicification, and sericitization, and is comparable to that of other VMS deposits. Most workers regard Eskay Creek as having characteristics of both epithermal and VMS deposit-types (MacDonald et al., 1996; Sillitoe et al., 1996). The comparatively low tonnage, which is significantly smaller than that of Archean deposits, is compensated by the much higher ore grade.

Associated Mineral Deposit Types

Gold-rich VMS deposits are thought to have formed under a variety of conditions. At one end of the spectrum, they are thought to represent the shallow water equivalents of subaerial epithermal Au deposits (Hannington, 1993; Poulsen and Hannington, 1996, Sillitoe et al., 1996) (Fig. 19). These may coexist regionally with Au-poor VMS deposits (e.g. Horne), and could also possibly coexist with deposits of the epithermal clan (including deposits of the high-sulphidation type) and intrusion-related Au deposits formed lower in the stratigraphic sequence (Sillitoe et al., 1996; Hannington et al., 1999) (e.g. Doyon mine in the Doyon-Bousquet-LaRonde district) (Fig. 1). As there is an empirical relationship between large Au-rich VMS deposits and major fault zones (e.g. LaRonde Penna and Horne with the Cadillac-Larder Lake fault), they may coexist with syndeformation Au deposits of various types, including greenstone-hosted quartz-carbonate veins.

Genetic and Exploration Models

Conventional Models

Gold-rich VMS deposits have been the subject of much controversy during the last 20 to 30 years, particularly the timing of Au deposition (synvolcanic or syntectonic) relative to the formation of the massive sulphide orebody. Consequently, their origin remains questioned (Arnold and Sillitoe, 1989; Poulsen and Hannington, 1996; Sillitoe et al., 1996; Huston, 2000, and references therein), especially in metamorphosed Precambrian terranes (Valliant and Hutchinson, 1982; Stone, 1988; Stone et al., 1988; Tourigny et al., 1989; Marquis et al., 1990a,b,c; Bergman Weihed et al., 1996). As discussed by Poulsen and Hannington (1996), there are basically two genetic models: 1) conventional syngenetic volcanic-hosted Au-poor base metal mineralization overprinted during regional-scale deformation and metamorphism by syndeformation Au mineralization (Tourigny et al., 1989, 1990; Marquis et al., 1990a,b,c; Yeats and Groves, 1998); and 2) syngenetic VMS deposits that differ from the conventional massive sulphide deposits by an anomalous fluid chemistry and/or deposition within a shallow-water to subaerial volcanic setting (Poulsen and Hannington, 1996; Hannington et al., 1996; Sillitoe et al., 1996; Huston, 2000). In such a shallow-water environment, boiling may have had a major impact on the fluid chemistry, including its high Au enrichment relative to base metals, and its precipitation due to rapid change in pH and decrease in temperature (Poulsen and Hannington, 1996). In some cases, Au-rich VMS deposits are thought to represent a transition between abyssal base metal-rich seafloor sulphide deposits and subaerial high-sulphidation epithermal Au deposits; as such, they are considered the submarine equivalent to subaerial high-sulphidation epithermal deposits (Poulsen and Hannington, 1996; Sillitoe et al., 1996; Hannington et al., 1999; Huston, 2000).

In the case of a syndeformational Au mineralization overprinting conventional VMS deposits, the key geological features in support of such a model include location of deposits in highly deformed and metamorphosed sequences close to regional-scale faults, the presence of sulphide veins that are discordant to regional foliations, and ore zones that locally are parallel to foliation (Doyon-Bousquet-LaRonde district) (cf. Tourigny et al., 1989; Marquis et al., 1990a,b,c) or transposed along a discordant post-ore shear zone (or high-strain zone), as illustrated at Boliden.

In the synvolcanic Au-rich VMS deposits model, regional metamorphism and deformation have served only to modify the geometry of the deposit, and its mineralogy by locally

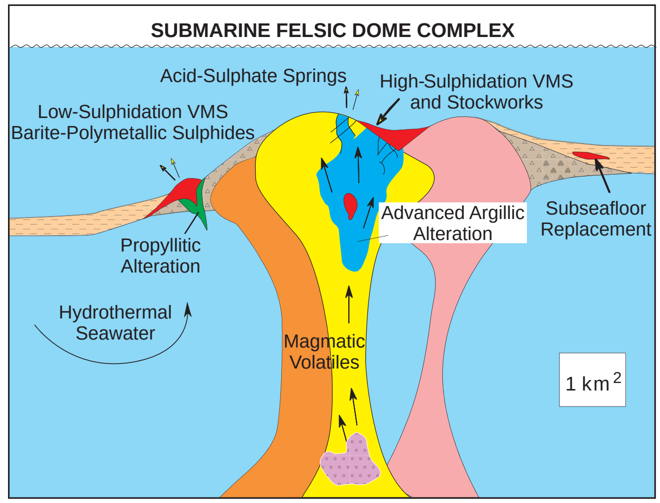

Figure 19. Schematic section showing the position of high- and low-sulphidation volcanogenic massive sulphide environments in relationship to the submarine volcanic setting (from Sillitoe et al., 1996).

redistributing some of the constituents into structurally controlled sites (Valliant and Barnett, 1982; Tourigny et al., 1993; Dubé et al., 2004, in press). The world-class Eskay Creek deposit contains relatively undeformed Au-Ag orebodies that undoubtedly have exhalative affinities (Poulsen and Hannington, 1996). Furthermore, in a re-examination of the geology of the Horne deposit, Kerr and Mason (1990) offered evidence against a late-tectonic superposition of Au. Foremost among these are the observations that, locally, an unmineralized debris flow has unconformably cut down into the Au-Cu mineralization, and that otherwise barren pyroclastic tuffs in the stratigraphic hanging-wall contain Au-rich blocks of underlying massive sulphides. The Horne orebodies also contain elevated Au concentrations (e.g. >3 g/t Au) over intervals in excess of several tens of metres (Barrett et al., 1991). In some districts, the Au-rich VMS deposits occur within the same stratigraphic sequences and adjacent to Au-poor VMS deposits. For example, the Au-rich orebody at Montauban contains substantial quantities of base metals and occurs along strike from the Montauban Zn-Pb orebody (Poulsen and Hannington, 1996). The base metal deposits are considered by most geologists to be of VMS-type. If one accepts the exhalative nature of the deposits, the most relevant inquiry is to the nature of the parameters that distinguish base metal massive sulphide deposits that contain little Au from auriferous base metal massive sulphide deposits that have a relatively high base metal to Au ratio (Poulsen and Hannington, 1996).

Recent work in the Doyon-Bousquet-LaRonde district demonstrates that the Bousquet Formation (2699-2697 Ma) of the Blake River Group has played a key role in the formation of the Au-rich VMS lenses (Dubé et al., 2004, in press; Mercier-Langevin et al., 2004; Lafrance et al., 2005; Mercier-Langevin, 2005). Although almost all volcanic contacts (hiatus) host massive sulphide lenses or transposed stringers, the largest VMS lenses are located in the upper transitional to calc-alkaline portion of the Bousquet Formation (Dubé et al., 2004; Mercier-Langevin et al., 2004; Lafrance et al., 2005). The large LaRonde Penna deposit is thought to be, at least in part, genetically related to rhyo-

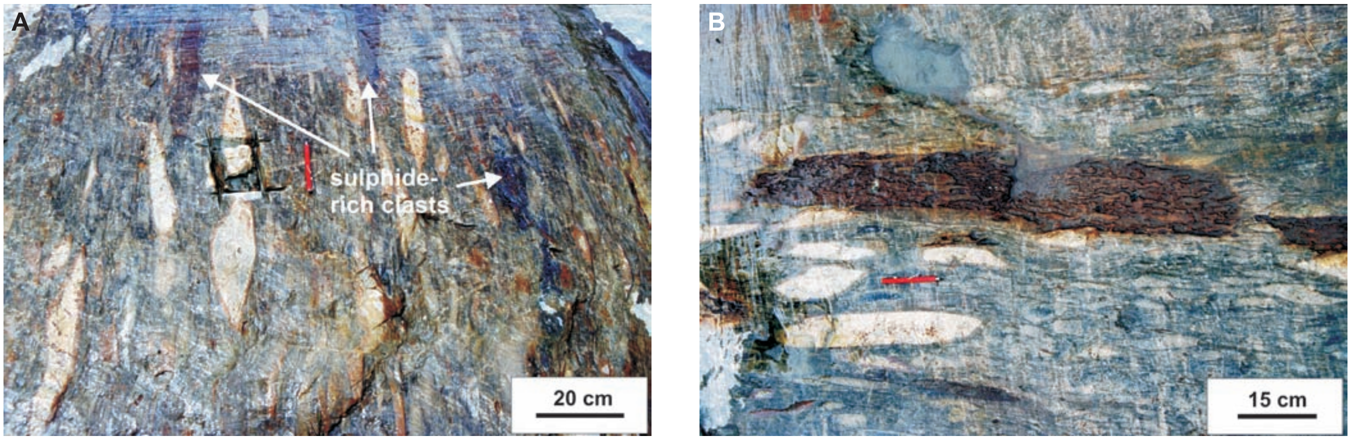

Figure 20. (A) Sulphide-rich clasts within a debris-flow stratigraphically above the massive sulphides lens number 6 mined at LaRonde No. 2 shaft. **(B)** Close-up of a sulphide-rich clast.

dacitic to rhyolitic calc-alkaline domes, and to the presence of gabbroic to dioritic high-level sills-dykes (known as andesite) and blue quartz-bearing rhyolites in its hanging wall, which are believed to have acted as a less permeable cap. The presence of Au-bearing sulphide-rich clasts (up to 6 g/t Au) in a debris flow stratigraphically above a massive sulphide lens (lens number 6) mined at LaRonde shaft No. 2 is definitive evidence of pre-deformation Au-rich VMS mineralization (Mercier-Langevin, 2005; Fig. 20A,B).

The impact of regional structures on the primary synvolcanic control on the distribution of the mineralization is well illustrated in the Doyon-Bousquet-LaRonde district, where a number of large orebodies of varying size, type, and preservation are located about 1 km apart (Mercier-Langevin et al., 2007c). They plunge steeply towards the southwest, parallel to the main stretching lineation (L2). The spacing of the deposits in the camp is thought to be controlled by synvolcanic faults, whereas their plunge result from a combination of factors including the superimposed main stage of D2 deformation (Dubé et al., 2003). Detailed mineralogy and trace element geochemistry of the ore and alteration at LaRonde Penna demonstrated that synvolcanic Au and base metals have been locally remobilized and concentrated during superimposed deformation-metamorphism events (Dubé et al., 2004). Despite extensive metamorphic recrystallization and deformation, a crude metal zoning of Cu, Zn, Pb, Ag, and Au, which mimics primary metal zonation in less deformed massive sulphides, is still evident in the massive sulphide lenses (Dubé et al., 2004; Mercier-Langevin, 2005). The intimate association of Au with the base metals, both at LaRonde Penna and in the nearby Bousquet 2-Dumagami Au-Cu-Zn orebody, is evidence for the existence of an auriferous polymetallic protore from which strongly remobilized Au-bearing sulphides were derived (Teasdale et al., 1996; Mercier-Langevin, 2005). Remobilized, auriferous chalcopyrite veins, which have previously been considered to be products of syntectonic Cu-Au mineralization (Marquis et al., 1990a), contain locally abundant sphalerite, pyrrhotite, and galena and merge with foliation-parallel massive sulphides of similar mineralogy, suggesting that the structurally controlled Au-rich ores are mainly products of local metamorphic remobilization. Partial replacement of pyrite by remobilized chalcopyrite has been suggested as evidence for the late-stage introduction of Cu and Au (Marquis et al., 1990a). However, pressure-solution effects such as these are a common feature of metamorphosed massive sulphide ores and do not require that new Cu was added during metamorphism (Dubé et al., 2004, and references therein). Other trace elements that are intimately associated with Au (e.g. Bi, As, and Te) are enriched in the ores, but no more than in many other Archean Cu-Zn VMS deposits. There is clear textural evidence for remobilization of Ag, Pb, Bi, and Sb minerals together with Au in the chalcopyrite veinlets surrounding large pyrite porphyroblasts. However, remobilized constituents of the ores do not appear to have moved beyond the margins of the orebodies and the primary metal zonation of Pb, Cu, and other elements has been preserved (Dubé et al., 2004). The implication is that these elements were likely present in the original ores at their current levels and have simply been concentrated in metamorphically remobilized sulphides during deformation (Dubé et al., 2004). Thus, the Au-base metal association at the LaRonde Penna strongly suggests the formation of a polymetallic Au-VMS system (Dubé et al., 2003). Synvolcanic Au and base metals have been locally remobilized and concentrated during superimposed deformation-metamorphism events as proposed by Tourigny et al. (1993) and Teasdale et al. (1996) for the nearby Bousquet 2-Dumagami deposit.

Two end-member explanations for primary Au enrichments in VMS deposits are proposed (Poulsen and Hannington, 1996). One is where the hydrothermal fluid is dominated by evolved seawater from which local boiling has caused the deposition of significant Au. In this case, the resulting auriferous base metal massive sulphide deposit should have few distinguishing field parameters compared to Au-poor massive sulphides. Another scenario is one where corrosive leaching by acidic, relatively oxidized, and sometimes sulphur-rich fluids (from disproportionation of magmatic SO_2?) that may be of magmatic origin (Hedenquist and Lowenstern, 1994; Sillitoe et al., 1996), mixed with and diluted by seawater, contributes to high-Au enrichment relative to base metals. Hydrothermal alteration types (i.e. sericitic and advanced argillic) are therefore more typical of subaerial magmatic hydrothermal systems (high-sulphidation epithermal). Both conditions may be encountered in an emerging (or submerging) volcanic arc (Fig. 21). This model is attractive in that it allows for regional coexistence of Au-poor with Au-rich massive sulphide deposits (Poulsen and Hannington, 1996; Sillitoe et al., 1996; Hannington et al., 1999).

Advances in Genetic/Exploration Models of the Last Decades

Gold-rich VMS deposits, like other VMS deposits, occur at major lithological contacts that mark a hiatus or a distinctive change in volcanic and sedimentary facies (e.g. the rhyolite-andesite contact at Horne, and the dacite/rhyodacite-andesite contact at LaRonde Penna and Bousquet 2-Dumagami). In the Doyon-Bousquet-LaRonde district, the emplacement of intermediate to felsic domes could have provided the magmatic heat source in the immediate environment and may also have contributed part of the Au to the system (Mercier-Langevin et al., 2007a,b). Proximity to transitional to calc-alkaline volcanic centres is a key element in terms of exploration in this district (Dubé et al., 2004, in press; Mercier-Langevin et al., 2004). Other Au-VMS deposits may be located in districts that host VMS deposits that are not particularly Au-rich (e.g. Horne in the Noranda district, and Boliden in the Skellefte district). Depending on shape and depth, the sulphide contents of many of these deposits are sufficient to produce geophysical responses. Airborne and ground electromagnetic methods are effective at detecting massive sulphide mineralization but only where the sulphide grains are electrically connected. If they are not, they are, from an electromagnetic point of view, considered as disseminated sulphides; in which case they should be detectable by induced polarization surveys (Poulsen and Hannington, 1996).

At a local scale, the presence of aluminous alteration (originally proposed by Valliant et al., 1983), with a mineral assemblage characterized by andalusite, kyanite, and staurolite with Mn-rich garnet, is a useful exploration guide to some Au-VMS deposits, such as Bousquet 1 and Bousquet 2-Dumagami, LaRonde Penna, Boliden, and Au-rich VMS deposits in ancient metamorphosed terranes (Dubé et al., 2004, in press). Because of their ductility, these alteration zones have accommodated most of the post-ore strain and are commonly transformed into schists and transposed subparallel to high-strain zones. Consequently, the alteration will coincide with deformation zones regardless of genetic and age relationships. Aluminous schists with anomalous Au and/or zinc values in intermediate to felsic, transitional to calc-alkaline volcanic or volcaniclastic products located underneath a sedimentary cover, represent excellent exploration targets (Dubé et al., in press). However, exploration strategies for Au-rich VMS must consider the diverse metal content and zonation of alteration minerals even within a single hydrothermal system. All the Au-rich VMS lenses are not associated exclusively with aluminous alteration (Hannington et al., 1999; Huston, 2000; Dubé et al., 2004; Mercier-Langevin, 2005). The quartz-biotite-Mn-rich garnet alteration zone in transitional to calc-alkaline dacites-rhyodacites represents a first order alteration footprint especially well developed in the footwall of some large VMS lenses, such as in the upper and intermediate parts of 20 North zone at LaRonde Penna. However, the andalusite- and kyanite-rich aluminous alteration is a key ore host or vector towards

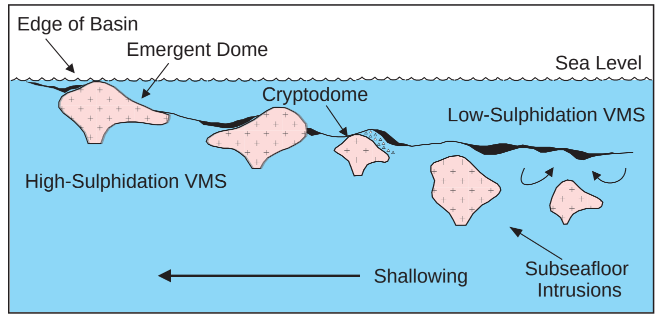

FIGURE 21. Development of high-sulphidation versus low-sulphidation conditions in a submarine setting in relation to the depth of emplacement of associated subvolcanic intrusions (from Hannington et al., 1999).

the ore at depth at LaRonde Penna and at Bousquet 2-Dumagami (Marquis et al., 1990c; Tourigny et al., 1990, 1992; Dubé et al., 2004, in press). Thus, there are potentially significant 3-D variations in the hydrothermal alteration and mineralization styles even within a single deposit; exploration strategies for Au-rich VMS deposits should take this diversity into account (Dubé et al., 2004, in press).

Knowledge Gaps

The reason(s) why some districts or specific rock formations are so prolific and contain major Au-rich VMS deposits adjacent to Au-poor VMS deposits remains one of the most critical questions to be addressed. The best example is the Archean Blake River Group (2701-2696 Ma; Lafrance et al., 2005) of the Abitibi subprovince: it yielded slightly more than 755 t of Au, which represents 85% of the production and reserves for this subtype of Au deposits in Canada. The Blake River Group is, therefore, a particularly important exploration target for this style of Au deposit (Dubé et al., 2003). It also hosts many conventional VMS deposits (Gibson and Watkinson, 1990). The geochemical composition and volcanic facies of the Au-rich VMS-hosting Bousquet Formation of the Blake River Group, as well as its geological setting, are key elements responsible, at least in part, for the formation of the district (Lafrance et al., 2003; Dubé et al., 2004, in press; Mercier-Langevin et al., 2004; Mercier-Langevin, 2005). However, more work remains to be done to fully understand the unique Au endowment of this particular volcanic group (e.g. Mercier-Langevin et al., 2007c). As proposed by Hodgson (1993) and Huston (2000), it is also possible that the “provinciality” of the VMS deposits high-Au grade may be related to specific fundamental geological characteristics in terms of favourable source-rock environments or Au reservoirs. The local geological “heritage” (endowment) of the district, in addition to ore-forming processes, may indeed be a major factor to take into account.

The role played by synvolcanic and subvolcanic intrusions, such as the 2700 +3/-2 Ma Flavrian-Powell subvolcanic intrusive complex (Galley and Van Breemen, 2002) near Horne, or the multistage Mooshla intrusion in the Doyon-Bousquet-LaRonde district, remains to be better defined. The synvolcanic Mooshla intrusion (2696.9 ±1 Ma) (Lafrance et al., 2005) is contemporaneous to the upper member of Bousquet Formation and hosts intrusion-related pre-main stage deformation quartz- and sulphide-rich veins at the Doyon mine (Gosselin, 1998; Galley et al., 2003; Galley and Lafrance, in press). Despite its relatively small size, it has been proposed that the Mooshla intrusion may have provided metals and/or the thermal effect needed to initiate or maintain the hydrothermal fluid circulation (Valliant and Hutchinson, 1982).

At the district scale, the two largest Canadian Au deposits of this type (Horne and LaRonde Penna) are located a few kilometres from the Cadillac-Larder Lake fault. This empirical relationship between such a crustal-scale fault and the synvolcanic VMS mineralization remains intriguing.

The presence in some Au-rich VMS deposits of metamorphosed, advanced argillic (aluminous) and massive silicic alteration, indicative of an oxidized, low-pH hydrothermal fluid, has been used to suggest an analogy between some Au-VMS and high-sulphidation epithermal deposits (Hannington, 1993; Sillitoe et al., 1996; Hannington et al., 1999, and references therein). In such cases, the Au-rich VMS deposits are interpreted as shallow-water submarine equivalents to subaerial epithermal deposits. However, direct magmatic input into the hydrothermal fluid(s) responsible for the formation of Au-VMS deposits with high-sulphidation affinity remains to be demonstrated, as well as the source of the low-pH characteristic of the fluid. Also, as pointed out by Huston (2000), the shallow-water setting proposed for Au-VMS deposits is often difficult to establish clearly and field criteria to better define the water depth in ancient metamorphosed settings need to be improved. Deformation and metamorphism that commonly overprint mineralization in ancient terranes have induced transposition and local remobilization of Au, and sometimes base metals, into structures adjacent to the original massive sulphide lenses. This has obscured the original relationships and led to considerable debate about syntectonic versus synvolcanic origin for the formation of the deposits and/or their Au content (e.g. Boliden). In some cases, deformation is so severe that it is extremely difficult to define the exact chronology of events, the timing of Au precipitation, and whether the deposit is the end product of superimposed hydrothermal systems. A definitive conclusion about the timing of mineralization with respect to deformation and metamorphism is often impossible. The use of new geochronological techniques, such as Re-Os dating of arsenopyrite, may help resolve the debate (Huston, 2000). This new technique may provide the age of a sulphide phase that is directly associated with the mineralization and which sometimes hosts the Au. Combined with field relationships and U-Pb dating of the host sequence, Re-Os age determination of pyrite and/or arsenopyrite (Arne et al., 2001) could consequently determine the exact timing of Au precipitation within a VMS deposit and contribute to the debate between the syntectonic versus synvolcanic model.

Acknowledgements

This synthesis has been made possible by the kind cooperation of numerous companies, governments, and university geologists who shared their knowledge and who have allowed surface and underground tours of many Au deposits. We benefited from numerous discussions with colleagues from the provincial surveys, in particular Géologie Québec, and from the Geological Survey of Canada. The first author would like to extend his deepest appreciation to F. Robert and H.K. Poulsen for constructive suggestions, collaboration, and discussions on Au deposits during the last twenty years as well as to Agnico-Eagle Mines Ltd., Barrick Gold Corp., and Cambior Inc. for their support and great collaboration. W. Goodfellow and I. Kjarsgaard are thanked for their editorial contribution. Careful constructive reviews by M. Jébrak, W. Goodfellow, G. Beaudoin, and S. Castonguay have led to substantial improvements.

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