GOLD-RICH VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS

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Definition

Definition of Gold-rich Volcanogenic Massive Sulphide Deposits

Simplified definition

A lens of iron-, copper-, zinc- and lead-sulphides, with significant amounts of silver and gold, formed on or below the sea floor by hot springs on and around submarine volcanoes.

Scientific definition

Gold-rich volcanogenic massive sulphide deposits (Au-VMS) are a sub-type of both volcanogenic massive sulphide (VMS) and lode gold deposits (Poulsen and Hannington, 1996; Hannington et al., 1999; Huston, 2000; Poulsen et al., 2000) (Fig.1). Like most VMS deposits, they consist of semi-massive to massive, concordant sulphide lenses underlain by discordant stockwork feeder zones. The main difference between Au-VMS and other VMS deposits is their gold concentration (in g/t Au), which exceeds the associated combined Cu, Pb, and Zn grades (in weight per cent). Gold is thus the main commodity. However, the polymetallic nature of this deposit sub-type makes it more resistant to fluctuating metal prices, resulting in a very attractive exploration target.

Several gold-rich VMS deposits discussed by Hannington et al. (1999) and Huston (2000) are not included within this sub-type of gold deposits as their gold to base metal ratio is too low.

The Au-VMS deposits are present in both recent seafloor and deformed and metamorphosed submarine volcanic settings. In the latter, they may contain local syntectonic quartz-sulphide or rarely quartz-tourmaline veins which can 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

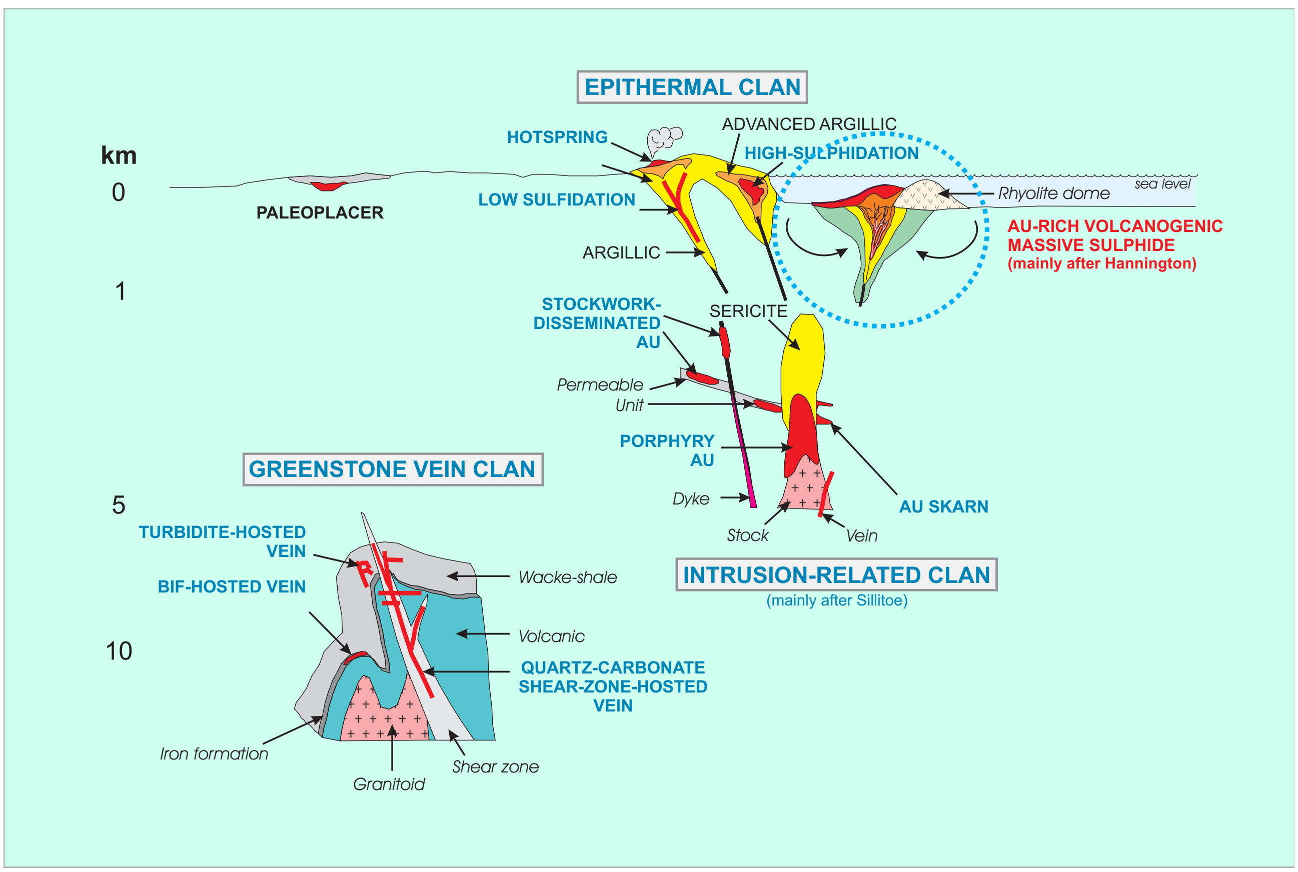

FIG. 1: Schematic illustration of the various types of gold deposits shown at their inferred crustal levels of formation. (Dubé et al., 2001, modified from Poulsen et al., 2000).

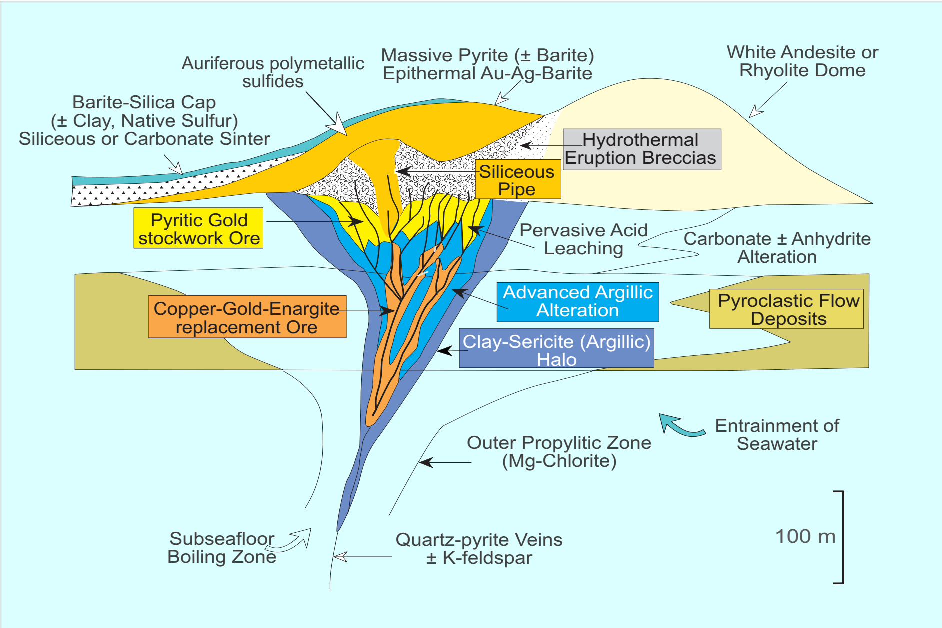

FIG. 2: Schematic illustration of geological setting and hydrothermal alteration associated with Au-rich high-sulphidation VMS hydrothermal systems (from Hannington et al., 1999).

commonly underlain by coeval sub-volcanic intrusions and sill-dyke complexes, typically metamorphosed to greenschist and lower amphibolite facies in greenstone belts of various ages. The gold most commonly has an uneven distribution within the deposit due to both primary depositional controls and subsequent tectonic remobilization. The gold-metal association varies from Cu-Se-Bi through Zn-Pb to Ag-Cu-As-Sb-Hg. Some Au-VMS deposits are characterized by metamorphosed advanced argillic (aluminous) 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. When 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-VMS deposits are interpreted as shallow-water submarine equivalents to the sub-aerial epithermal deposits (Hannington, 1993; Sillitoe et al., 1996; Hannington et al., 1999; Fig. 2).

There are presently only thirteen world-class (>30 t Au in production and reserves) Au-VMS deposits in the world (Fig. 3, Table 1). One of the best examples is Boliden (Sweden) (Grip and Wirstam, 1970; Bergman-Weihed et al., 1996). Many are located in Canada: the large Horne (Cu-Au) deposit, the Bousquet 2 - LaRonde 1 (Au-Ag-Cu-Zn) and the LaRonde -Penna (Au-Zn-Ag-Cu) deposits (Quebec), and the

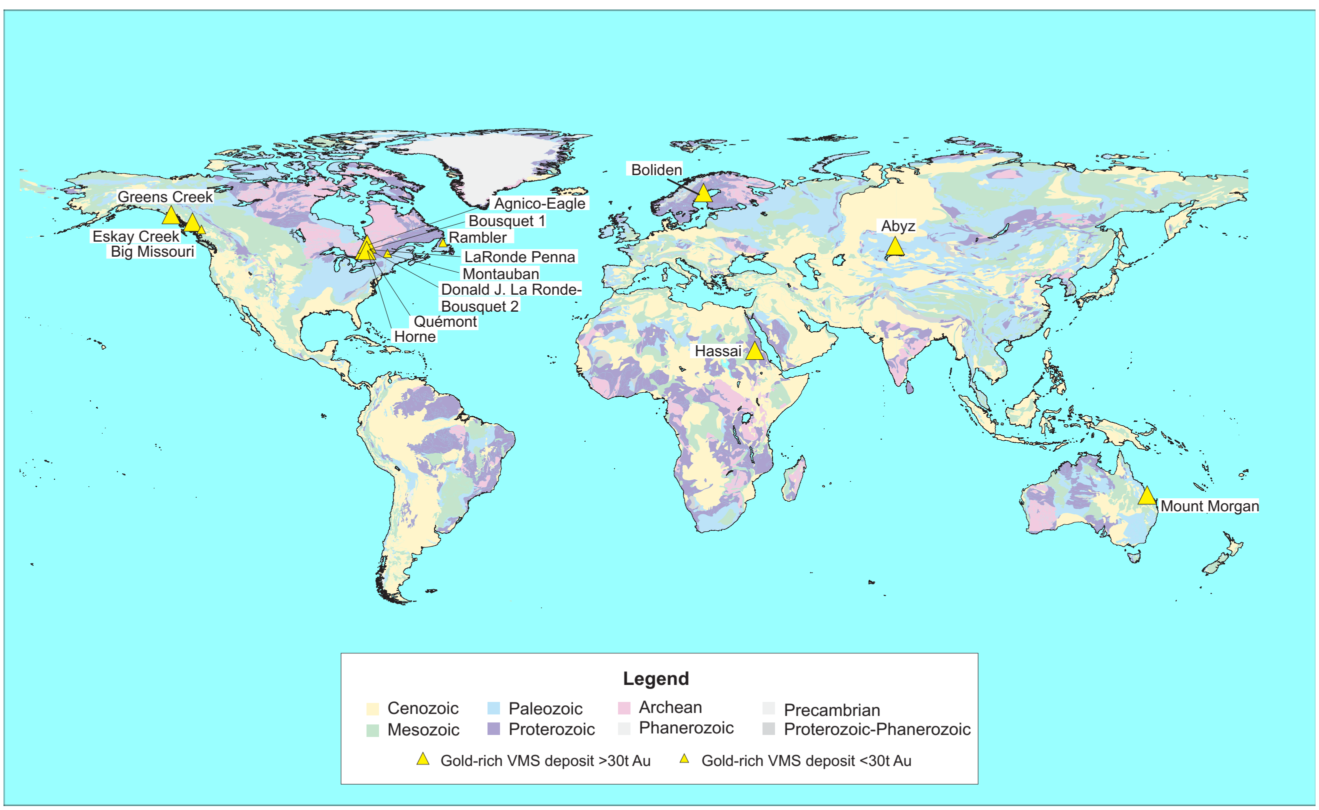

FIG. 3: Map showing locations of world-class Au-VMS deposits containing at least 30 tonnes Au.

Table 1: Grade and tonnage of world-class Au-VMS deposits with at least 30 tonnes Au in production and reserves

Deposit name	Country	Tonnage (Mt)	Au (g/t)	Ag (g/t)	Cu (%)	Pb (%)	Zn (%)
Bousquet 1	Canada	6.44	5.55				
Agnico Eagle	Canada	6.93	5.18				
Bousquet 2 - LaRonde 1	Canada	23.26	5.14	2.12			
Horne	Canada	54.3	6.10	13.00	2.22		
LaRonde Penna	Canada	43.45	4.23	52.12	0.32		2.72
Quemont	Canada	13.92	4.74	19.53	1.21		1.82
Eskay Creek	Canada	2.49	44.38	2087.68			
Mt. Morgan	Australia	80.74	3.67	0.74	0.72		
Hassai	Sudan	6.2	10.00				
Boliden	Sweden	8.3	15.09	48.31	1.42		
Abyz	Kazakhstan	4.4	6.47	61.00	2.13		5.35
Greens Creek	U.S.A.	11.2	4.20	560.94	0.01	4.07	10.88

Eskay Creek (Au-Ag-Cu-Zn-As-Sb-Hg) deposit (British Columbia). Compared to the overall gold production from other deposit types, the total gold production from Au-VMS is small but locally highly significant, as in the Blake River Group of the Abitibi greenstone belt, that hosts most of the Canadian deposits. The Horne Mine is the largest Au- VMS deposit mined so far with 331 t Au produced, and LaRonde Penna is the largest gold deposit presently being mined in Canada. Cumulative production until December 31, 2003 was 771 616 oz Au from 5,712 364 t of ore at 4.20 g/t Au, 62.08 g/t Ag, 3.21% Zn, and 0.29% Cu. Reserve and global resources as of December 31, 2003 are evaluated at 8.37 M oz Au from 60.7 Mt of ore (Agnico-Eagle Ltd. Annual Report 2003).

Diagnostic features of Au-rich VMS deposits

The diagnostic features of submarine gold-rich volcanogenic massive sulphide gold deposits are strata-bound volcanic-hosted massive sulphide bodies with associated discordant stockwork stringer feeder zones (Fig. 4) in which gold grades (in g/t) exceed associated combined Cu, Pb, and Zn grades (in percent). Felsic to intermediate volcanic rocks and associated volcaniclastic products and subvolcanic tonalitic intrusions are common at the district scale (e.g. Bousquet 2 - LaRonde 1 and LaRonde Penna). Metamorphosed advanced argillic products (aluminous alteration with andalusite) may be common at the deposit scale.

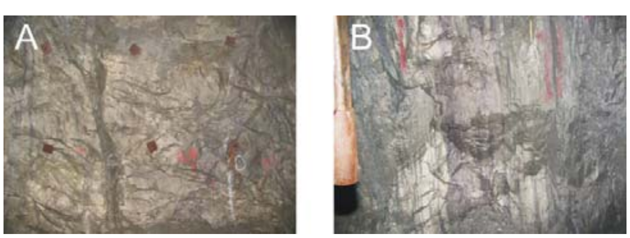

FIG. 4. A: Massive pyrite zone, lens 20 North LaRonde Penna; section shown is 3m wide; B: Massive pyrite with layers of sphalerite, lens 20 South, LaRonde Penna; section shown is 2m wide.

Associated Mineral Deposit Types

The Au-VMS sub-type of gold deposits is thought to form under a variety of conditions. At one end of the spectrum, Au-VMS deposits are thought to represent the shallow water equivalents to sub-aerial epithermal gold deposits (Hannington, 1993; Poulsen and Hannington, 1996, Sillitoe et al., 1996) (Fig. 5). These examples may coexist regionally with Au-poor VMS deposits, and could also coexist with deposits of the epithermal clan including deposits of the high-sulphidation type, and intrusion-related gold deposits formed lower in the stratigraphic sequence (e.g. Doyon Mine in the Doyon-Bousquet-LaRonde district) (Fig. 1).

Economic Characteristics of Au-Rich VMS Deposits

The total world production and reserves of gold, including the Witwatersrand placer deposit, is 120,689 metric tonnes, whereas the Canadian production and reserves are 9,276 metric tonnes (7.7%). The world production and reserves for the submarine Au-rich VMS deposit sub-type is 1453 metric tonnes of Au, equivalent to 1.2% of the world production and reserves. The Canadian production and reserves for Au-VMS is 894 metric tonnes, less than 1% of the world production and 9.6% of the Canadian production and reserves. The Blake River Group of the Abitibi subprovince contains 739 metric tonnes of Au, which represents 83% of the production and reserves for that sub-type of gold deposits in Canada, and 13.4% of the known gold in the Abitibi greenstone belt. The Blake River Group, in particular within the Doyon-Bousquet-LaRonde district, is therefore an important setting for this style of gold deposit.

Grade and Tonnage Characteristics

The size of Au-VMS deposits ranges from small sulphide lenses with less than 2 t of gold in 2-10 Mt deposits, to giant-sized lenses and stockwork-stringer zones of >50 Mt containing over 300 t of gold. Tonnage varies from small

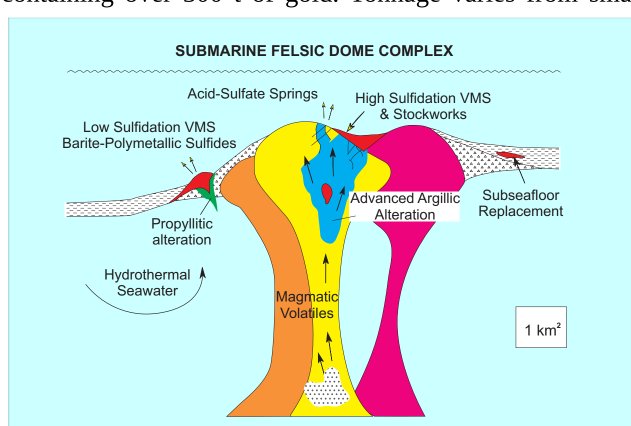

FIG. 5. Schematic section, showing the position of high and low sulphidation volcanogenic massive sulphide (VMS) environments in relationship to the submarine volcanic setting (from Sillitoe et al., 1996).

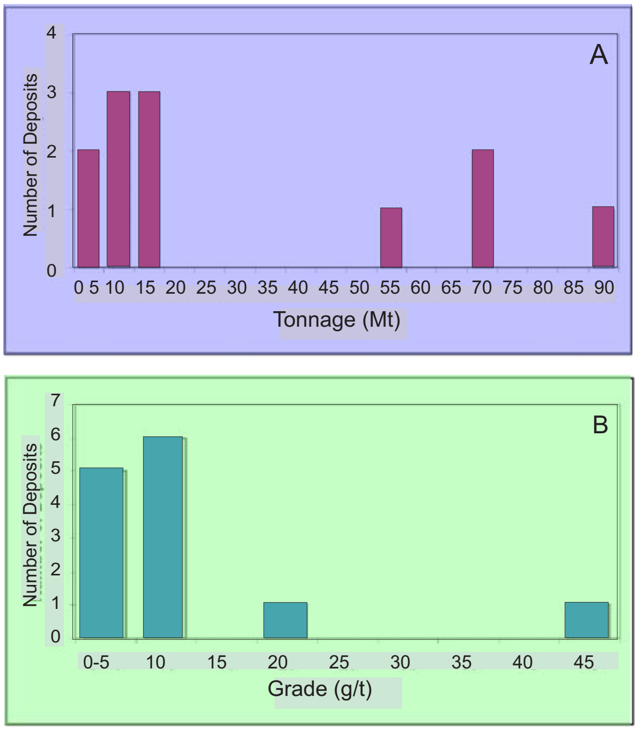

FIG. 6: Histograms of tonnage (A) and grade (B) for Au-VMS deposits worldwide.

lenses of 6 Mt of ore to >85 Mt at Mount Morgan (Australia) (Fig. 6a). The typical grade is greater than 4 g/t, with one deposit (Eskay Creek) reaching as high as 43 g/t (Fig. 6b, Fig. 7). Some of the largest Au-VMS deposits are Canadian: Horne (331 t of Au), LaRonde Penna (184 t) and Bousquet 2 - LaRonde 1 (134 t). Other world-class deposits are Mount Morgan (Australia, 296 t) and Boliden (Sweden, 125 t), and the less well-known Abyz deposit (Kazakhstan, 29 t) (Fig. 7).

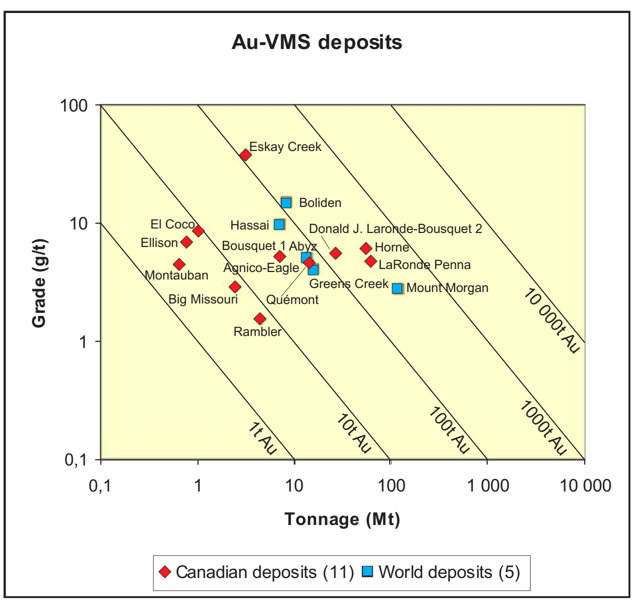

FIG. 7: Grade vs. tonnage of all Canadian Au-VMS deposits and five international world-class (>30 t Au) deposits (numbers include production, reserves and resources).

Comparison of Grade and Tonnage Characteristics with the Global Range

There are only 12 known submarine VMS gold deposits worldwide that contain at least 30 tonnes (1 M oz) of Au (production and reserves) including 7 Canadian deposits (Table 1). A select group of 6 world-class deposits contains more than 100 tonnes of Au including two giant deposits with more than 250 tonnes (Horne and Mount Morgan; Fig. 7). The largest submarine Au-VMS deposit in terms of total gold content is the Horne deposit in the Rouyn-Noranda district, Quebec, with 331 t of gold produced from 54.3 Mt of ore at 6.1 g/t Au. The LaRonde Penna deposit (Doyon-Bousquet-LaRonde district) is the second largest Canadian and worldwide example with 285 tonnes of Au contained in 60.7 Mt ore at 4.69 g/t Au, including known resources. Average gold grade for the Canadian gold-rich VMS deposits is 7.83 g/t Au, which is slightly higher than the world average at 7.69 g/t, but may vary from 1.5 g/t up to 38 g/t.

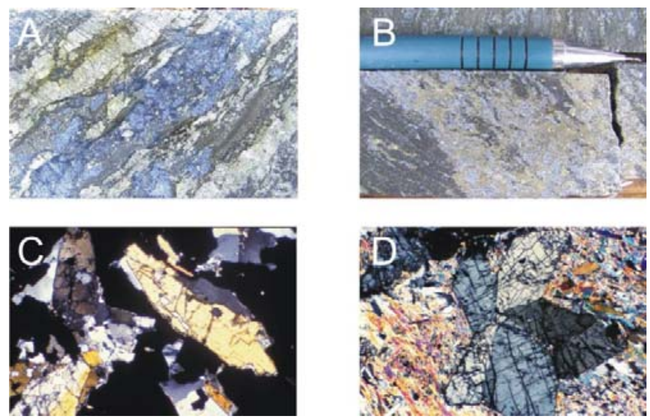

FIG. 8.A: Andalusite, kyanite, pyrite, chalcopyrite replacement ore zone, LaRonde Penna; B: Kyanite and pyrite-rich replacement-style ore zone, LaRonde Penna; C: Kyanite crystals (yellow, brown) in pyrite (black) and quartz (white, grey), LaRonde Penna (polarized light); D: Zn-rich staurolite (blue, grey and beige) in sericitic matrix, LaRonde Penna (polarized light).

Exploration Properties of Au-VMS Deposits

Physical Properties

<u>Mineralogy</u>

The mineralogy of gold-bearing and associated minerals is highly variable, which is typical of all types of VMS deposits. In metamorphosed greenstone terranes, the gangue minerals may include quartz, sericite, aluminous silicates such as andalusite, kyanite and Zn-rich staurolite, and Mn-rich garnet (Sillitoe et al., 1996; Huston, 2000 and references therein) (Fig. 8). Huston (2000) proposed that the advanced argillic alteration is more typical of the Au-Cu sub-class of Au-VMS deposits, whereas potassic feldspar is more typical of the Au-Zn-Pb-Ag association.

The sulphide mineralogy of the gold-bearing ores is commonly more complex than in traditional gold-poor VMS deposits (Hannington et al., 1999). Sulphide minerals are mainly pyrite (Fig. 4) and base-metal sulphides (chalcopyrite, sphalerite, galena) with a complex assemblage of minor

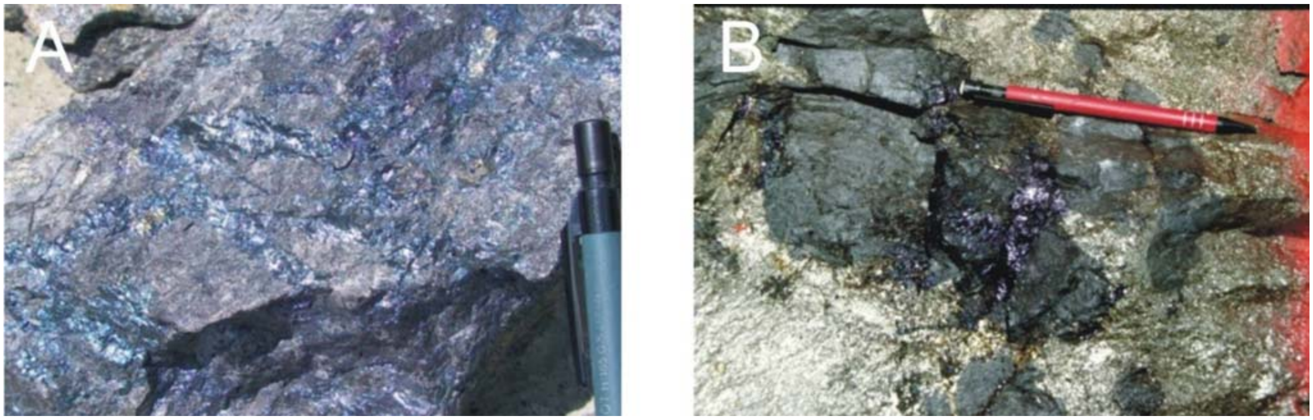

FIG. 9. A: Bornite veins cutting across highly silicified dacite (Bousquet 2 mine); B: Bornite veinlets cutting highly silicified clast within massive pyrite lens (Bousquet 2 mine).

phases including locally significant amounts of bornite (Bousquet 2 - LaRonde 1 and Boliden; Fig. 9), tennantite, sulphosalts, arsenopyrite, mawsonite and tellurides (Table 2). The strong association of tellurides with gold suggests a magmatic input. The Boliden deposits contained nearly 50 different ore minerals whereas more than 25 major and trace minerals have been identified in the ores at LaRonde 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. 10; 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., 1999). The 21A zone consists of strata bound to stratiform lenses of semi massive to massive stibnite and realgar whereas the 21B zone is a stratiform sulphide-sulphosalt zinc-lead-gold silver zone. The sedimentary textures of the stratiform 21B zone are consistent with its detrital origin (Fig. 11) (Poulsen et al., 2000). It is clearly distinct from the other Au-VMS deposits.

As indicated by Hannington et al. (1999), gold is present mainly as the native metal and as Au-tellurides in copper-gold deposits, whereas auriferous polymetallic sulphides (Au-Zn-Pb-Ag) typically contain electrum, which is often Ag-rich or mercurian (e.g. Huston et al., 1992). In some deposits, gold is mainly hosted in arsenic-rich pyrite and arsenopyrite, commonly refractory and present as submicroscopic inclusions or structurally bound in the crystal lattice (Huston et al., 1992; Larocque et al., 1993; and references therein). In metamorphosed deposits such as LaRonde, metamorphic remobilization and segregation has had a major impact on the distribution of gold in the ores and has played an important role in generating non-refractory gold minerals (Dubé et al., 2004). At LaRonde, free gold, as electrum, accounts for the majority (>90%) of the gold in the ores (Dubé et al., 2004). The gold grains are typically very fine (1-5 microns) and occur mainly as inclusions in recrystallized pyrite and in chalcopyrite within microfractures in recrystallized pyrite. The electrum typically occurs intimately intergrown with other remobilized trace minerals (Fig. 10b).

<u>Textures</u>

Banded and stratiform massive-sulphide lenses and adjacent stockworks are commonly transposed by the main foliation in deformed and metamorphosed deposits. In such cases, syntectonic sulphide veins could have developed, which add to the complexity of the deposits.

<u>Dimensions</u>

The vertical extent of the stockwork is typically larger than the lateral extension. In some cases where the deposits are overturned the ore body has more than 2 km of known

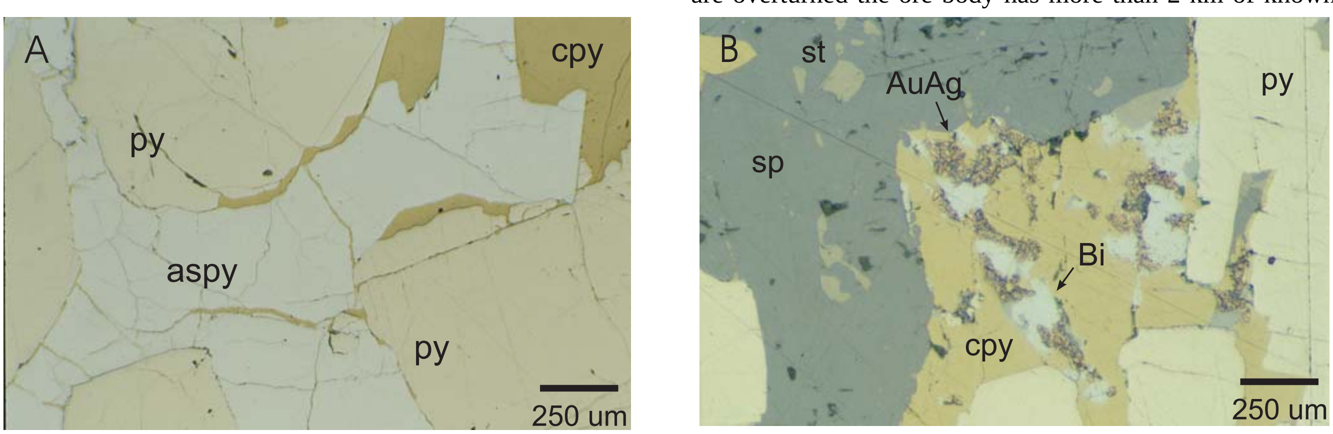

FIG 10: Photomicrographs showing typical ore textures and mineral assemblages of the different ore zones in the LaRonde mine (aspy: arsenopyrite; AuAg: electrum; Bi: bismuthite; cpy: chalcopyrite; po: pyrrhotite; py: pyrite; sph: sphalerite; st: stannite (from Dubé et al., 2004).

Table 2. Mineralogy of the LaRonde deposit and selected Au-rich VMS in the Doyon-Bousquet-LaRonde district[1].

LaRonde[1]	Bousquet 2	Dumagami	Bousquet 1
Major Minerals[3]:			
Pyite	Pyrite	Pyrite	Pyrite
Pyrrhotite	Chalcopyrite	Chalcopyrite	Chalcopyrite
Chalcopyrite	Bornite	Sphalerite	
Sphalerite			
Galena			
Minor Minerals:			
Arsenopyrite	Sphalerite	Galena	Sphalerite
Tetrahedrite (Ag)	Galena	Arsenopyrite	Pyrrhotite
Stannite	Tennantite (Te)	Bornite	Magnetite
Magnetite	Chalcocite	Chalcocite	Arsenopyrite
	Pyrrhotite	Covellite	Galena
	Magnetite	Digenite	Bornite
Trace Minerals:			
Electrum	Electrum	Electrum	Elelctrum
Hessite	Hessite	Altaite	Au-Telluride
Native Bi	Petzite	Cu-Ag-sulfide	Altaite
Bi-telluride[4]	Altaite	Stannite	Stannite
Ag-Bi-sulfide	Tellurobismuth	Alabandite	Gudmundite
Cu-Pb-Bi-sulfide	Mawsonite		
Pb-Sb sulfosalts	Colusite		
Ag-Sb sulfosalts	Renierite		
Gudmundite			
Clausthalite			
Colusite			
Scheelite			
Cassiterite			

[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]Selected mineral formulas (alphabetical): bornite Cu_5FeS_4; silver tetrahedrite $Cu_{12}(Sb,Ag)_4S_{13}$; tellurian tennantite $(Cu,Zn,Fe)_{13}(As,Sb,Te)_4S_{12}$; arsenopyrite FeAsS; hessite Ag_2Te; petzite Ag_3AuTe_2; calaverite $AuTe_2$; altaite PbTe; clausthalite PbSe; tellurobismuth Bi_2Te_3; tetradymite Bi_2Te_2S; stannite Cu_2FeSnS_4; stannoidite $Cu_8(Fe,Zn)_3Sn_2S_{12}$; mawsonite $Cu_6Fe_2SnS_8$; colusite $Cu_{26}V_2(As,Sn,Zn,Ge)_6S_{32}$; renierite Cu_3GeFeS_4, covellite-digenite CuS, alabandite MnS, gudmundite FeSbS

[4]Bi-telluride = joseite-like compositions Bi_4Te_2S; Ag-Bi-sulfide = mathildite $AgBiS_2$; Cu-Pb-Bi-sulfide = wittichenite Cu_3BiS_3 and unidentified Mn-Bi-Pb-Sb sulfosalt; Pb-Sb sulfosalts = boulangerite $Pb_5Sb_4S_{11}$ and bournonite $PbCuSbS_3$; Ag-Sb sulfosalts = dyscrasite Ag_3Sb.

vertical extension (Horne and LaRonde Penna deposit). The thickness of the massive sulphide lenses is highly variable but commonly in the order of a few tens of meters.

Morphology

The typical morphology of Au-VMS deposits consists of a lenticular massive sulphide body with associated discordant stockwork-stringer feeders and replacement zones (Fig. 12A). Some deposits such as LaRonde Penna contain stacked massive sulphide lenses. The ore bodies are commonly tabular and stratiform and are located at the contact between felsic-intermediate volcanics or volcaniclastics and basaltic andesite. In most cases they have been deformed and tilted, and have a foliation-parallel pipe-like geometry due to

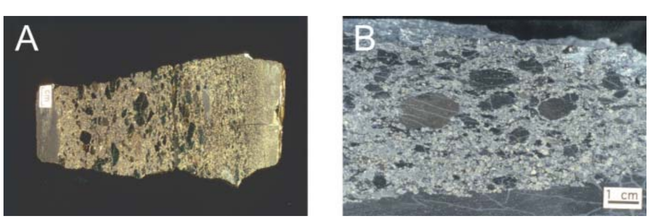

FIG. 11. A: Graded sulphide-silicate turbidite bed; B: Tetrahedrite-rich (light grey) sedimentary debris flow containing siliceous argillite clasts (dark grey to black); both photographs from the 21B zone, Eskay Creek (Poulsen et al., 2000).

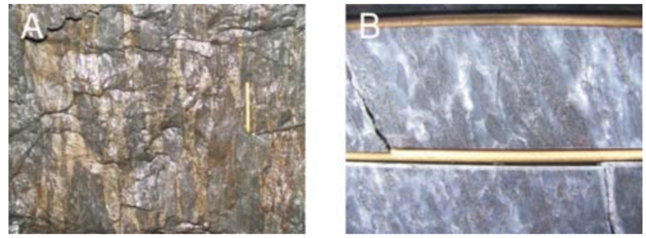

FIG. 12. A: Pyrite-rich stringers zone underneath lens 20 South, LaRonde Penna; B: Quartz-andalusite-muscovite-pyrite schist, Bousquet 2 mine.

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.12B). At Horne, zones of auriferous sulphide veinlets with Fe-chlorite selvages account for some of the gold-rich ore (Kerr and Mason, 1990), however, the deposit lacks a well-defined stringer zone (Poulsen et al., 2000). At Mt. Morgan, the gold is restricted to pyrite-rich vein systems that cut the earlier-formed massive sulphide lens. A similar situation exists in the Doyon deposit (Quebec), where early VMS mineralization is overprinted by a telescoped epithermal deposit associated with high-level emplacement of subvolcanic intrusions (Galley et al., 2003).

Host rocks

The mineralization is hosted by felsic volcanic flows, tuffs and volcaniclastic rocks (or their metamorphosed equivalents) near or at the interface with basalt-andesite or clastic sedimentary strata (e.g. LaRonde-Penna, Eskay Creek, Boliden) (Fig. 13).

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. 14). It is juxtaposed against andesite flows and a diorite intrusion to the south, and calc-alkaline rhyolites to the north, which contain the Quemont deposit, another auriferous massive sulphide deposit (Poulsen et al., 2000).

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, Se, Te and Hg. At Eskay Creek, Sb, As, Hg and Ba are characteristic of the high-grade ore (Roth et al., 1999). When associated with Cu, Au is commonly concentrated within the

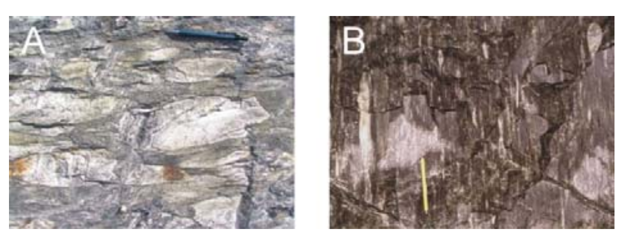

FIG. 13. A: Rhyodacitic talus breccia in footwall of 20 North massive sulphide lens, LaRonde Penna; B: Rhyodacitic lapilli tuff (unit 5.5) in the footwall of the 20 South massive sulphide lens, upper Bousquet Formation, LaRonde Penna.

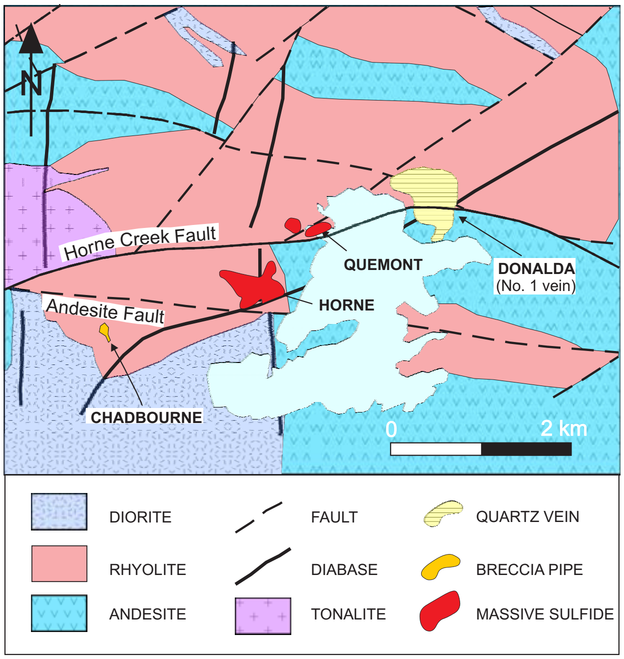

FIG. 14: Simplified map of the geology around the Horne deposit, Rouyn-Noranda district. Modified from Cattalani et al. (1993). Quartz veins and massive sulphide deposits are projected to surface (From Poulsen et al., 2000).

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). When 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). Silver is commonly more abundant than Au; Ag/Au ratios typically vary from 1:2 to 10:1.

Alteration Mineralogy/chemistry

In the Doyon-Bousquet-LaRonde district, semi-conformable to discordant zones of metamorphosed advanced argillic (aluminous) alteration with quartz, sericite, andalusite and/or kyanite pyrophyllite, and local massive silicic alteration with strong to complete leaching of Na, Ca, Mg and K, commonly characterize the alteration assemblages proximal to or hosting the ore (Figs. 15A, B). An outer quartz-manganiferous garnet-staurolite-chloritoid-biotite-muscovite-chlorite assemblage is present further away from the mineralization, especially in its footwall (Fig.15C). Green mica may be locally present (e.g. LaRonde Penna, 20 South lens; Dubé et al., 2004; Fig.15D). The North and South ore zones at Montauban are associated with disseminated pyrite-sphalerite-chalcopyrite with cordierite-anthopyllite and quartz-biotite garnet assemblages within quartz-biotite and quartz-sillimanite gneiss (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 sub-class of Au-VMS, whereas potassic feldspar is more typical of those characterized by the Au-Zn-Pb-Ag association.

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

Geological Properties

Geotectonic Setting

Continental scale: Au-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 and lower amphibolite facies, and intruded by sub-volcanic intrusions and dyke-sill complexes. The deposits are associated with, and commonly located in proximity of intermediate to felsic volcanic centers, at or close to the interface between intermediate to felsic volcanic domes (and associated volcaniclastic products) and basalt-andesite or clastic sediments. Their host strata are commonly underlain by coeval sub-volcanic intrusions and sills or dykes. The tectonic setting is commonly inferred to be that of island arcs, rifted arcs, back-arc basins or back-arc rifts (Hannington et al., 1999; Huston, 2000). In modern volcanic settings, Au-VMS deposits are commonly associated with rifted-arc and incipient back-arc environments rather than mature back-arc spreading centers (Hannington et al., 1999). According to these authors, an association with rifted continental crust and continental margin arc environments may be particularly important in some cases (e.g. Boliden, Eskay Creek).

District scale: Au-VMS deposits are located in greenstone belts and arc-related environments of all ages. They coexist regionally with Au-poor VMS deposits and districts endowed with such deposits may well contain undiscovered Au-rich mineralization. Large volumes of effusive rhyolite and associated felsic pyroclastic rocks (lithic tuffs, crystal

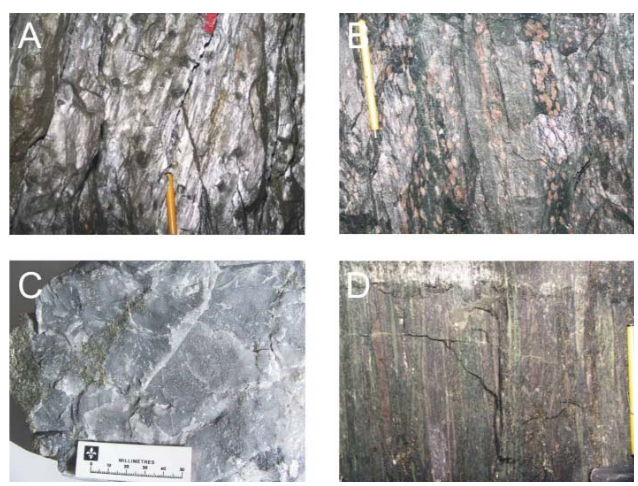

FIG. 15. A: Quartz-muscovite-andalusite schist in the footwall of the 20 North lens, LaRonde Penna; B: Deformed Mn-rich garnet-biotite alteration zone at the base of the 20 North lens, LaRonde Penna mine; C: Massive silicic alteration (97% SiO_2) cut by pyrite stringers at the base of the massive sulphide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

tuffs, etc.) and the presence of numerous subvolcanic intrusions or dyke swarms of tonalitic to granitic composition (Hannington et al., 1999) are also important features of Au-VMS deposits. In particular, apophyses developed on oxidized granitoids may be important (Huston, 2000). Areas of transitional subaerial to shallow submarine volcanism are potentially very prospective. Shallow-water volcanic complexes can be traced most readily through detailed mapping of volcanic and sedimentary facies (Hannington et al., 1999). Textures indicative of boiling may also be useful (Huston, 2000).

Evidence of syn-volcanic deformation (synvolcanic faults, horsts and fault-bounded blocks, variations in volcanic facies) can provide information on fluid channel ways and vents. Post-volcanic deformation and metamorphism often caused significant remobilisation of gold into faults and shear zones adjacent to the original sulphide lenses (Hannington et al., 1999). Pyritic quartz-sericite schists are a common host rock, and are indicative of acid alteration. Semi conformable zones of hydrothermal alteration are characterized by large aureoles of distal chloritic/propylitic (with sericite) alteration, surrounding more proximal zones of intense acid alteration near the deposit. These proximal zones may be characterized by sericitic to silicic/advanced argillic/aluminous alterations; the latter alteration is believed to be a metamorphosed equivalent of an argillic/advanced argillic alteration halo (Hannington et al., 1999).

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

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

Deposit scale: The association of Au-VMS deposits with rhyolites and tonalitic to granitic subvolcanic intrusions make these rock types important targets for exploration. Gold mineralization can occur in strata bound massive sulphide lenses, but also in stockworks and disseminated sulphides hosted by subvolcanic intrusions and adjacent felsic volcanic rocks.

Where deposits are chemically or mineralogically zoned, gold may have been leached from the base and centers of massive sulphide lenses and reprecipitated at the top. Thus, variations in metal zonation, metal ratios, and ore thickness can be used to find the richest part of an ore body (Huston, 2000).

Faults, shears and veins, either within or adjacent to sulphide lenses, may contain remobilized gold or gold reintroduced during deformation/metamorphism. These may be attractive areas that can yield high gold grades.

Recognition of systematic mineralogical variations in alteration zones and distinctive proximal alteration assemblages, such as advanced argillite alteration and aluminous alteration, are important guides.

Possible geochemical anomalies depend on the deposit (Au-Cu versus Au-Zn-Pb-Ag associations: Huston, 2000). Most deposits show proximal depletion of Na, K, and MREE and enrichment of Cu, As, Mo, Bi, Te and LREE, with distal enrichment of Zn, Ca, Mn, and C as well as the epithermal suite of As, Sb, and particularly Hg.

Distribution of Canadian Au-VMS Districts

Due to the low number of Au-VMS deposits, there are relatively few districts containing Au-VMS deposits in Canada and around the world.

Districts listed in Table 3 contain Au-VMS deposits as well as other epithermal (low- or high-sulphidation) or intrusion-related deposits (Au-Cu sulphide-rich veins), and greenstone-hosted quartz-carbonate vein deposits. However, production, reserves and resource figures listed are for deposits of the Au-VMS sub-type only.

The Horne, Quemont and El Coco (Russian Kid) deposits are located in the Rouyn-Noranda district (see Fig. 16 for location of districts), which also contains a large number of greenstone-hosted quartz-carbonate vein and base-metal VMS deposits, which are not sufficiently enriched in gold to fall into the Au-VMS category.

The Doyon-Bousquet-LaRonde district hosts three producing mines (LaRonde Penna, Doyon and Mouska) and several past producers (Bousquet 1, Bousquet 2 - LaRonde 1 and 2, Mooshla A and B, and MicMac; Fig. 17). It is the second largest gold camp in Quebec and one of the most prolific Archean Au-VMS districts with more than 20.9 M oz Au (past production, reserves and resources). The LaRonde Penna deposit represents one of the largest complexes of gold-rich VMS lenses in the world. Production from the LaRonde Penna shaft began in June 2000. Cumulative production to December 31, 2002 is 699,375 oz Au from 4,341 915 tonnes at 5.01 g/t Au, 76 g/t Ag, 4.44 % Zn, and 0.27% Cu (G. Gosselin, Agnico-Eagle, personal communication, March 2003). Reserves and global resources are estimated at 8.08 M oz Au from 59.32 Mt (Agnico-Eagle News Release February 2003). The VMS deposits in the camp are hosted by the upper portion of the Blake River Group (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 of the district with 216 tonnes of Au in production and reserves. Early VMS mineralization at Doyon is overprinted by a telescoped epithermal deposit associated with high-level emplacement of subvolcanic intrusions. The only other mine in production is the orogenic quartz-carbonate Mouska deposit.

Table 3. List of Canadian Au -VMS districts

District	Geological province	Production+Reserves (tonnes Au)	Resources (tonnes Au)
Bousquet	Superior/Abitibi	339	135
Rouyn-Noranda	Superior/Abitibi	411	
Joutel	Superior/Abitibi	36	
Iskut River	Cordilleran	116	8
Montauban	Grenville	3	
Baie Verte	Appalachian	7	

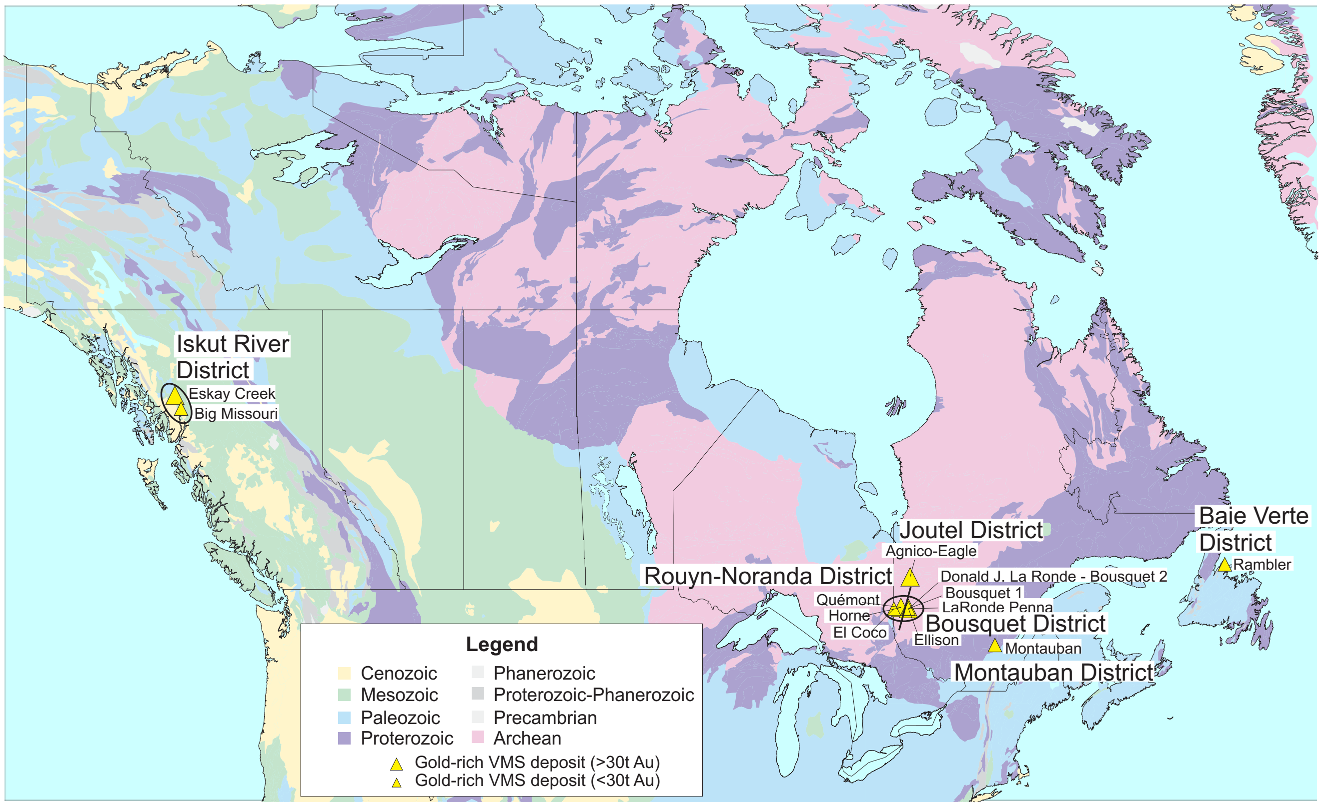

FIG. 16: Locations of Au-VMS districts in Canada.

The Iskut River district in British Columbia encompasses the high-grade Eskay Creek deposit (2.5 Mt at 44.4 g/t Au), and the smaller Big Missouri deposit (2.5 Mt at 2.9 g/t Au). Other significant deposits of this district are Au-Cu sulphide rich veins (Snip deposit, 32 t Au) and (mainly) low-sulphidation epithermal deposits (Silbak Premier, 65 t Au). 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 argillite and pillow basalt (Macdonald et al., 1996). The deposit consists of strata bound to stratiform lenses of semi-massive to massive stibnite and realgar (21 A Zone) and a stratiform sulpide-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 21 B Zone are consistent with a debris flow whereas the 21A Zone, with its underlying stockwork and disseminated ore zones, resembles epithermal mineralization. Alteration of the underlying volcanic rocks includes choritization, silicification and sericitization and is comparable to that of other volcanogenic massive sulphide deposits. Most workers regard Eskay Creek as having characteristics of both deposit types (Sillitoe et al., 1996; Macdonald et al., 1996). The comparatively low tonnage, which is significantly smaller than that of the Archean deposits, is compensated by the much higher grade of the ore.

The Joutel, Montauban and Baie Verte districts all have only one deposit of the Au-VMS sub-type. The Joutel district and Baie Verte have a number of other deposits of the greenstone-hosted, quartz-carbonate vein sub-type (e.g. Sleeping Giant, 25 t Au, and Stog'er Tight, 3.4 t Au, respectively). There are no other known gold deposits in the Montauban district.

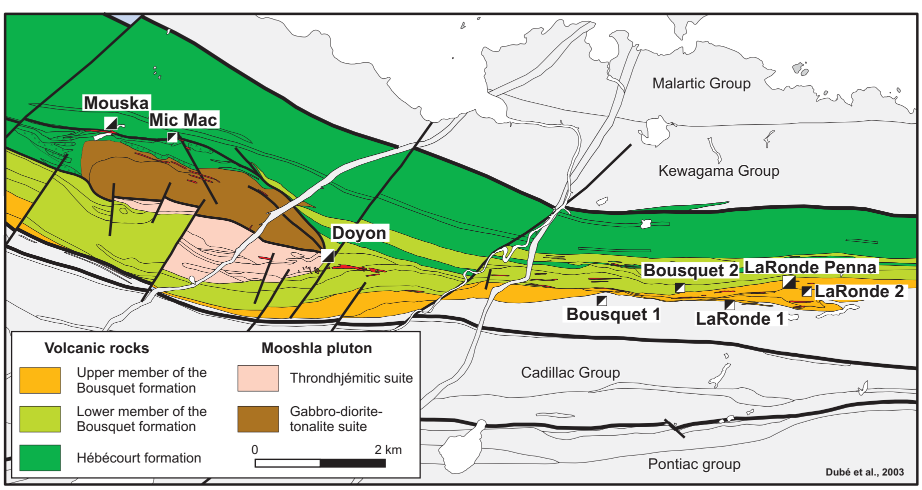

FIG. 17: Simplified geological map of the Doyon-Bousquet-LaRonde district showing the main geological features and the location of the mines (From Dubé et al., 2003).

Geological Distribution of Au-VMS Districts in Canada

Au-VMS deposits are distributed in areas where hydrothermal activity took place in tectonically active, arc- or back-arc-related seafloor environments. They are distributed in volcanic terranes located in orogenic belts and greenstone belts of various ages, frequently nearby major crustal-scale faults and large subvolcanic intrusions. In Canada, such settings are found in Archean greenstone belts within the Superior Province (Rouyn-Noranda, Doyon-Bousquet-LaRonde and Joutel districts), in the Paleozoic Dunnage zone of the Appalachians (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 environment.

Canadian deposits with a total gold content > 30 tonnes Au (world-class size) are located mainly in the Abitibi greenstone belt and are of Late Archean age (Fig. 18). Figure 18 also shows that the total gold content of the Canadian Archean Au-rich VMS deposits is larger than anywhere else. They have an average grade of 5.19 g/t Au and their tonnage ranges from 6.4 Mt (Bousquet 1) to 54.3 Mt (LaRonde Penna). The only Canadian deposit of Proterozoic age is the Montauban deposit (Grenville Province, Quebec), which has produced some 2.8 tonnes Au from ore grading 4.5 g/t. World-class Proterozoic examples are Boliden (Sweden) and Hassai (Sudan). A small Paleozoic deposit (Rambler deposit, Baie Verte district, Newfoundland) is located in a greenstone belt of the Dunnage zone (Appalachians) (Hibbard, 1983; Coates, 1990). It has produced some 6.9 tonnes Au from ore grading 1.54 g/t. The Rambler Main deposit is a volcanogenic polymetallic (Cu, Zn, Au, Ag) massive sulphide deposit, which occurs along the flank of a felsic dome (Coates, 1990). The deposit is hosted by felsic volcaniclastic rocks (dacitic tuffs, lapilli tuffs and agglomerates) overlain by mafic to intermediate flows and volcaniclastic rocks (Coates, 1990). As at LaRonde, a portion of the footwall of the Main Mine ore body at Rambler is characterized by gold-rich quartz-sericite-green micas schist with up to 4.8 g/t Au.

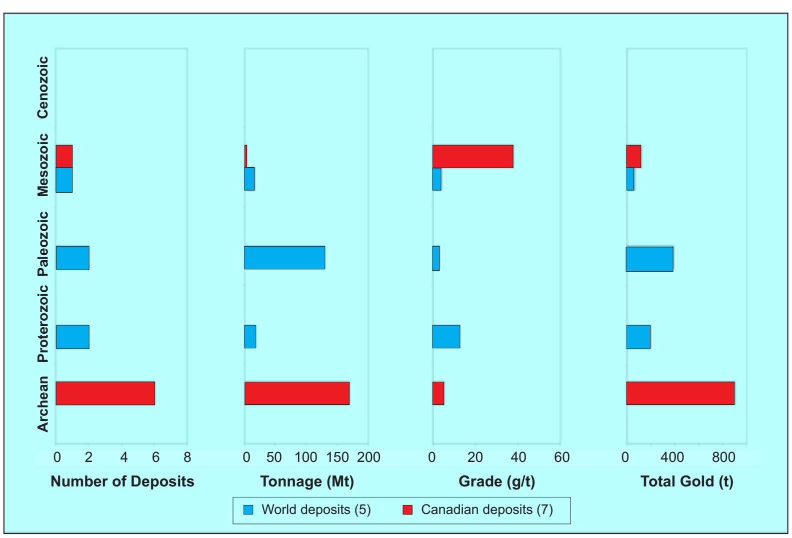

FIG. 18: Comparison of world-class Au-VMS deposits from different geological periods.

Other world-class Paleozoic deposits are Abyz (Kazakhstan) and the famed Mount Morgan mine (72.4 Mt at 4.1 g/t Au for 296 tonnes of gold) of Australia.

The Intermontane belt of the Canadian Cordillera hosts the Iskut River district with two deposits, one of which is the world-class Eskay Creek deposit, the other is the Big Missouri deposit. Greens Creek (11.2 Mt at 4.2 g/t), near Juneau, Alaska, is another example of a world-class Mesozoic Cordilleran deposit, this time in the Wrangellia terrane.

Genetic/Exploration Models

Conventional Models

Au-VMS deposits have been the subject of much controversy during the last 20-30 years, particularly the timing of gold deposition (synvolcanic or syntectonic) relative to the formation of the massive sulphide ore body. Consequently, their origin is controversial or 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 et al., 1988; Tourigny et al. 1989; Marquis et al, 1990a, 1990b, 1990c; Bergman-Weihed et al., 1996). As discussed in Poulsen and Hannington (1996), there are basically two genetic models: 1) conventional syn-genetic volcanic hosted gold-poor base metal mineralization overprinted during regional scale deformation and metamorphism by syn-deformation Au-mineralization (Tourigny et al., 1989, 1990; Marquis et al, 1990a, 1990b, 1990c; Yeats and Groves, 1998); and 2) syn-genetic VMS deposits that differ from the conventional massive sulphide deposits by an anomalous fluid chemistry and/or deposition within in a shallow water to subaerial volcanic setting in which boiling may have had a major impact on the fluid chemistry. In some cases they are thought to represent a transition between abyssal base-metal rich sea floor sulphide deposits and sub-aerial high-sulphidation epithermal gold deposits, and as such they are considered the sub-marine equivalent to sub-aerial high-sulphidation epithermal deposit (Poulsen and Hannington, 1996; Sillitoe et al., 1996; Hannington et al., 1999; Huston, 2000).

In the case of a syn-deformation gold mineralization overprint on conventional VMS mineralization, key geological features used to proposed such a model include the location of the deposit 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) or sub-parallel to fold axis (Boliden).

In the syn-volcanic Au-VMS deposits model, regional metamorphism and deformation have served only to modify the deposits and its mineralogy by locally redistributing some of the constituents into structurally controlled sites (Valiant and Barnett, 1982; Tourigny et al., 1993; Dubé et al., 2004). As indicated by Poulsen and Hannington (1996), the world-class Eskay Creek deposit contains relatively undeformed gold-silver ore bodies that undoubtedly have exhalative affinities. Furthermore, in a re-examination of the geology of the Horne deposit, Kerr and Mason (1990) offered numerous reasons why late-tectonic superposition of gold is unlikely. Foremost among these are the observation that, locally, an unmineralized debris flow has unconformably cut down into the gold-copper mineralization and that otherwise barren pyroclastic tuffs in the stratigraphic hanging-wall contain gold-rich blocks of underlying massive sulphides. The Horne ore bodies also contained elevated gold 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-VMS deposits occur within the same stratigraphic sequences and adjacent to Au-poor base metal deposits having all the attributes of volcanogenic massive sulphide deposits. For example, the gold ore body at Montauban contains substantial quantities of base metals and occurs along strike from the Montauban Zn-Pb ore body (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 a) base metal massive sulphide deposits that contain little gold from b) auriferous base metal massive sulphide deposits that have a relatively high base metal to gold ratio.

Recent work in the Doyon-Bousquet-LaRonde district demonstrates that the Bousquet Formation and especially its upper transitional to calc-alkaline members have played a key role in the formation of the Au-VMS lenses (Dubé et al., 2004). 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 (Lafrance et al., 2003; Dubé et al., 2004; Mercier-Langevin et al., 2004). The large LaRonde Penna deposit is thought to be, at least in part, genetically related to rhyodacitic to rhyolitic calc-alkaline domes and to the presence of gabbroic to dioritic high-level sills-dikes (known as andesite) in its hanging wall which are believed to have acted as a less permeable cap. Presence of gold-bearing sulphide-rich clasts (</= 6 g/t Au) in a debris flow stratigraphically above a massive sulphide lens (lens number 6) exploited at LaRonde shaft No. 2 is definitive evidence of pre-deformation Au-VMS mineralization. The impact of regional deformation on the primary syn-volcanic control on the distribution of the mineralization is well illustrated in the Doyon-Bousquet-LaRonde district where a number of large ore bodies of varying size, type and preservation are located 1,5 km apart. They plunge steeply towards the SW, parallel to the main stretching lineation (L2). The spacing of the deposits in the camp is thought to be controlled by synvolcanic caldera-ring faults, whereas its plunge results 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 demonstrate that synvolcanic gold 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 sulfides, is still evident in the massive sulfide lenses. The intimate association of gold with the base metals, both at LaRonde and in the nearby Bousquet 2 - LaRonde 1 Zn-Cu-Au ore body, is evidence for the existence of an auriferous polymetallic protore from which strongly remobilized gold-bearing sulphides were derived. Remobilized, auriferous chalcopyrite veins, which have previously been considered to be products of syntectonic Cu-Au mineralization (e.g. 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 gold-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 sulfide ores and do

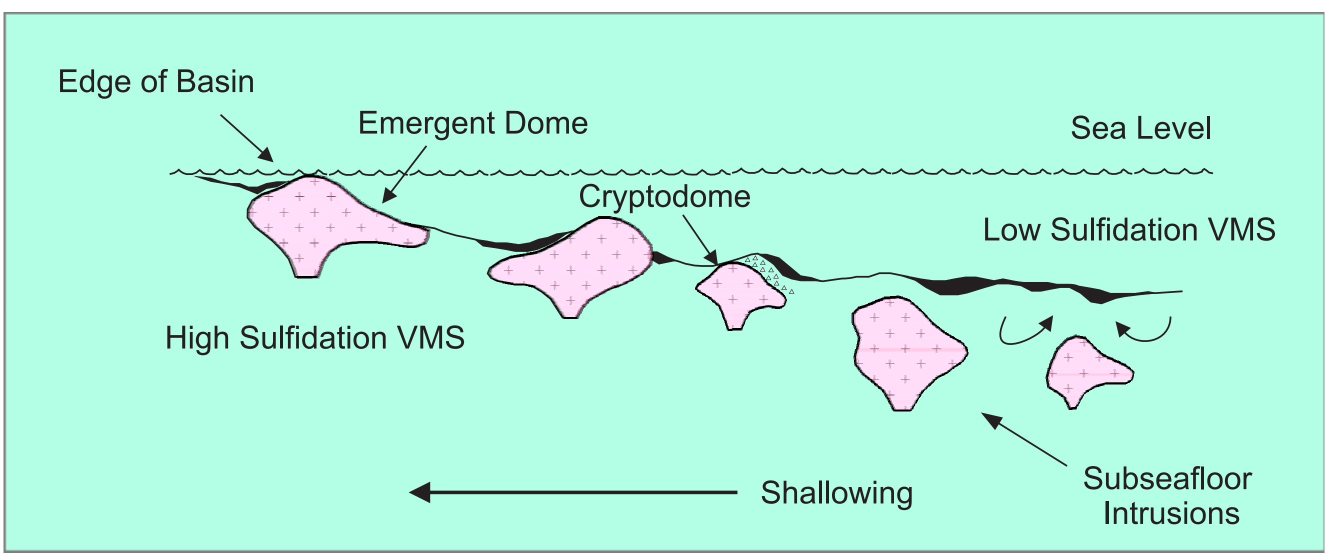

FIG. 19: Development of high-sulphidation vs. low-sulphidation conditions in submarine setting in relationships with the depth of emplacement of associated subvolcanic intrusions (from Hannington et al., 1999).

not require that new Cu was added during metamorphism (Dubé et al., 2004). 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 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 ore bodies and 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 sulfides during deformation. The gold-base metal association at the LaRonde Penna and Bousquet 2-LaRonde 1 Au-VMS deposits strongly suggests the formation of a polymetallic gold-rich volcanogenic massive sulfide system. Synvolcanic gold 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-LaRonde 1 deposit.

Two end-member explanations for primary gold enrichments in volcanic associated massive sulphide deposits are recognized (Poulsen and Hannington, 1996). One is where the hydrothermal chemistry is dominated by evolved seawater but that local boiling has allowed the deposition of significant gold. In this case, the resulting auriferous base metal massive sulphide deposits should have few distinguishing field parameters compared to gold-poor massive sulphides. Another scenario is one where unique acidic fluid chemistry (from magmatic sources?) contributes to both high gold enrichments relative to base metals and to alteration types (i.e. sericitic and advanced argillic) that are more typical of subaerial magmatic hydrothermal systems. Both conditions may be encountered in an emerging (or submerging) volcanic arc (Fig. 19). This model is attractive in that it allows for regional co-existence of gold-deficient massive sulphides with gold-rich varieties (Poulsen and Hannington, 1996, Sillitoe et al., 1996; Hannington et al., 1999).

Advances in Genetic/exploration Models of the Last Decade

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 in the Noranda district, the dacite/rhyodacite-andesite contact at LaRonde Penna and Bousquet 2-LaRonde 1 in the Doyon-Bousquet-LaRonde district). In the Doyon-Bousquet-LaRonde district, the emplacement of intermediate to felsic domes provided the magmatic heat source in the immediate environment and may also have contributed Au to the system. Proximity of transitional to calc-alkaline volcanic centres is a key element in terms of exploration in the district, as exemplified by the LaRonde Penna deposit (Dubé et al., 2004). Other Au-rich VMS deposits may be located in districts that host other massive sulphide deposits that are not particularly gold-rich (e.g. Horne in Noranda district, Agnico-Eagle in Joutel District, Boliden in Skellefte district etc.). The sulphide contents of many of these deposits are sufficient to produce geophysical responses and, owing to the disseminated to massive nature of the sulphides, induced polarization methods should be the most effective (Poulsen and Hannington, 1996).

At a local scale, the presence of aluminous mineral assemblages is a useful exploration guide to some types of Au-rich VMS such as Bousquet 1 and Bousquet 2-LaRonde 1, LaRonde Penna and Boliden. As originally proposed by Valliant et al. (1983), aluminous alteration with andalusite, kyanite and staurolite with Mn-rich garnet are key mineralogical assemblages for Au-VMS deposits of this type in ancient metamorphosed terranes (Dubé et al., 2004). Because of their ductility, these zones have accommodated most of the post-ore strain and are commonly transformed into schists and transposed sub-parallel to high-strained zones. Consequently, the alteration will coincide with deformation zones regardless of genetic relationships. Aluminous schists with anomalous gold and/or zinc values in intermediate to felsic, transitional to calc-alkaline volcanic or volcaniclastic products located underneath a sedimentary cover would be excellent exploration targets (Dubé et al., submitted). However, exploration strategies for Au-VMS must consider the diverse metal content and zonation of alteration even within a single hydrothermal system (e.g. LaRonde Penna). All the Au-VMS lenses are not associated exclusively with aluminous alteration. The quartz-biotite-manganese-rich garnet alteration zone in transitional to calc-alkaline dacites to rhyodacites represents a first order alteration commonly enveloping especially the footwall of the large VMS lenses such as the upper part of 20 North zone at LaRonde Penna. However, the andalusite-kyanite-rich aluminous alteration is a key vector towards or host for the ore at depth at LaRonde Penna and at Bousquet 2-LaRonde 1 (Dubé et al., 2004). Thus, there are potentially significant 3D variations in the hydrothermal alteration and mineralization styles. The exploration strategies for Au-VMS should take this diversity into account (Dubé et al., 2004), although the presence of massive to semi-massive sulphides is a critical element in terms of exploration (Hannington et al., 1999, Huston, 2000)

Knowledge Gaps

The reason why some districts or specific rock formations are so prolific and contain major Au-VMS deposits adjacent to gold-poor VMS deposits remains one of the most critical questions to be addressed. The best example in point is the Archean Blake River Group of the Abitibi subprovince. The Blake River Group contains 682 metric tonnes of gold, which represents 80% of the production and reserves for this sub-type of gold deposits in Canada, and 25% of the known gold in the Abitibi greenstone belt. The Blake River Group is, therefore, a particularly important exploration target for this style of gold deposit (Dubé et al., 2003). The Blake River Group also hosts many conventional VMS deposits. The reason(s) why these rocks are so prolific and contain such major Au-VMS deposits has been the subject of recent collaborative work in the Doyon-Bousquet-LaRonde district (Lafrance et al., 2003; Dubé et al., 2004;

Mercier-Langevin et al., 2004). The geochemical composition and volcanic facies of the Au-VMS hosting Bousquet Formation of the Blake River Group, as well as the geological setting, are key elements responsible, at least in part, for the formation of the district. However, more work remains to be done to fully understand the unique gold endowment of this particular volcanic group. As proposed by Hodgson (1993) and by Huston (2000), it is also possible that the "provinciality" of the high Au grade of the VMS deposits may be related to specific fundamental geological characteristics in terms of favourable source-rock environments or gold-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.

At the district scale, the two largest Canadian gold deposits of this type (Horne and LaRonde) are located a few km from the Larder-Cadillac fault. At first glance, only an empirical relationship could be invoked between such a crustal scale fault and the syn-volcanic VMS mineralization. However, the spatial relationship remains intriguing.

The presence in some Au-VMS deposits of metamorphosed advanced argillic (aluminous) and massive silicic alteration indicative of an oxidized low-pH hydrothermal fluid have been used to suggest an analogy between some Au-rich VMS and high-sulphidation epithermal deposits (Hannington, 1993; Sillitoe et al., 1996; Hannington et al., 1999 and references therein). In such cases, the Au-VMS deposits are interpreted as shallow-water submarine equivalents to the sub-aerial epithermal deposits. However, a direct magmatic input into the hydrothermal fluid(s) responsible for the formation of such Au-rich VMS deposits with high-sulphidation affinity remains to be demonstrated. Also, as pointed out by Huston (2000), the shallow-water setting proposed for Au-rich VMS deposits is commonly difficult to establish clearly and field criteria to better define the water depth in ancient metamorphosed settings need to be improved. The deformation and metamorphism that commonly overprint the mineralization in ancient terranes have induced transposition and locally remobilization of gold, 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 gold content. In some cases the deformation is so severe, that it is extremely difficult to define the exact chronology of events, when gold was precipitated and if 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. As suggested by Huston (2000), the use of new geochronological techniques such as dating arsenopyrite by Re-Os may help resolve the debate. This new technique may produce the age of a sulphide phase that is directly associated with the mineralization and which sometimes host the gold. Combined with field relationships and U-Pb dating of the host sequence, Re-Os age determination of arsenopyrite could consequently determine the exact timing of the gold precipitation within the VMS deposit and help resolve the debate between syn-tectonic vs. synvolcanic model.

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