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Critical review

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Abstract: The Cambro-Ordovician bimodal-mafic Ming Cu-Au-(Zn-Ag) volcanogenic massive-sulphide deposit is a type example of an Appalachian precious metal-enriched volcanogenic massive-sulphide deposit. The footwall of the deposit comprises at least three distinct felsic volcanic and volcaniclastic units. The immediate hanging wall is lithologically heterogeneous, comprising a highly silicified volcaniclastic rock and a magnetite-rich volcanogenic siltstone. Three generations of mafic to intermediate sills and dykes intrude the deposit and have distinctive lithogeochemical signatures; they are interpreted to be genetically related to the mafic rocks in the ophiolitic cover sequence that overlies the deposit.

The Ming deposit has distinct hydrothermal alteration mineral assemblages including: chlorite-quartz-epidote, sericite–quartz-green mica, quartz-pyrite, and Mn-garnet–calcite. Other minor secondary phases include biotite, tremolite, and magnetite. A Cu-rich zone consisting primarily of chalcopyrite, pyrrhotite, and pyrite with minor Bi-Te sulphosalt minerals and sphalerite in a strongly chlorite-quartz-epidote-altered felsic volcanic rock occurs 50 m to 100 m below the main sulphide lens, and represents the high-temperature discharge zone of the Ming hydrothermal system. An overprint of metamorphic biotite is ubiquitous throughout the felsic footwall rocks and represents metamorphosed K-Fe-(Mg) alteration to upper greenschist facies.

Despite local remobilization of the sulphide minerals due to deformation and metamorphism, the relationship between the host rocks, the alteration assemblages and their spatial distribution, and the ore strongly favour a syngenetic origin for the sulphide zones and their base and precious metals, suggesting intrinsically precious metal–enriched volcanogenic massive-sulphide ore-forming fluids at the Ming mine.

Résumé : Le gisement de Cu-Au-(Zn-Ag) de Ming, un gisement de sulfures massifs volcanogènes de type bimodal mafique du Cambro-Ordovicien, est un exemple type de gîte de sulfures massifs volcanogènes enrichi en métaux précieux des Appalaches. L'éponte inférieure du gisement est constituée d'au moins trois unités distinctes de roches volcaniques et volcanoclastiques felsiques. L'éponte supérieure immédiate est hétérogène du point de vue lithologique et est constituée de roches volcanoclastiques très silicifiées et de siltstone volcanogène riche en magnétite. Trois générations de filons-couches et de dykes mafiques à intermédiaires pénètrent le gisement et ont des signatures lithogéochimiques distinctes; on estime que ces intrusions sont liées génétiquement aux roches mafiques de la séquence de couverture ophiolitique qui surmonte le gisement.

Le gisement de Ming compte des associations distinctes de minéraux d'altération hydrothermale, notamment les suivantes : chlorite-quartz-épidote, séricite-quartz-mica vert, quartz-pyrite et grenat manganésifère-calcite. Les autres phases secondaires de moindre importance comprennent la biotite, la trémolite et la magnétite. Une zone riche en cuivre, constituée principalement de chalcopyrite, de pyrrhotite et de pyrite avec une petite quantité de sulfosels de Bi-Te et de sphalérite, dans des roches volcaniques felsiques présentant une forte altération à chlorite-quartz-épidote, se trouve entre 50 et 100 m sous la principale lentille de sulfures et représente la zone d'échappement des fluides de haute température du système hydrothermal de Ming. Une surimpression de biotite métamorphique est omniprésente dans les roches felsiques de l'éponte inférieure et représente une altération à K-Fe-(Mg) métamorphisée au faciès des schistes verts supérieur.

Malgré la remobilisation locale des sulfures produite par la déformation et le métamorphisme, la relation entre les roches encaissantes, les associations minérales d'altération et leur répartition spatiale, ainsi que le minerai plaident fortement en faveur d'une origine syngénétique pour les zones de sulfures et leurs métaux communs et précieux, ce qui donne à penser que les fluides minéralisateurs responsables du dépôt des sulfures massifs volcanogènes à la mine Ming étaient intrinsèquement enrichis en métaux précieux.

INTRODUCTION

Volcanic-associated hydrothermal events in ancient and modern submarine environments result in the formation of stratabound to stratiform accumulations of sulphide minerals referred to as volcanogenic massive-sulphide (VMS) deposits and seafloor volcanogenic sulphide deposits (SMS). They are formed at or near the ocean floor in various tectonic settings (e.g. mid-ocean rift, arc, back arc) and consequently occur in a wide variety of host-rock lithologies (e.g. Franklin et al., 1981, 2005; Hannington et al., 1999). Some volcanogenic massive-sulphide deposits are enriched in precious metals, with Au contents (in grams per tonne) that typically exceed the associated Cu+Pb+Zn grades (in weight per cent) (e.g. Poulsen and Hannington, 1996; Mercier-Langevin et al., 2011). The origin of the Au enrichment in these anomalous volcanogenic massive-sulphide deposits is commonly debated (e.g. syngenetic versus metamorphic overprint). Where Au-rich or auriferous volcanogenic massive-sulphide deposits occur in deformed and metamorphosed volcanic settings, they may be characterized by features that are epigenetic (e.g. overprinting Au-bearing syntectonic veins and fractures, structurally discordant ore zones, etc.), giving the impression that gold was introduced late in those deposits, leading to a postvolcanogenic massive-sulphide gold enrichment interpretation (e.g. Tourigny et al., 1989; Yeats and Groves, 1998). In other cases, workers argue that the enrichment is due to syngenetic processes and/or magmatic contributions (e.g. Hannington et al., 1999; Huston, 2000; Dubé et al., 2007a; Mercier-Langevin et al., 2007, 2013, 2014). Although they can both occur within the same district, the setting of Au-rich volcanogenic massive-sulphide systems and associated hydrothermal alteration assemblages differ somewhat from 'Au-poor' volcanogenic massive-sulphide deposits (e.g. Sillitoe et al., 1996; Dubé et al., 2007a). Therefore, in districts where the origin of gold enrichment in the deposits is debated, it is important to constrain factors that possibly control the variation in metal content and the origin of precious-metal enrichment (e.g. volcano-stratigraphy, lithology, deformation, and geodynamic setting; Mercier-Langevin et al. (2011)).

The host rocks commonly associated with Au-rich volcanogenic massive-sulphide deposits are felsic volcanic and volcaniclastic rocks that are near, or at the interface with, mafic-intermediate volcanic or clastic sedimentary rocks (Dubé et al., 2007a). In the general volcanogenic massive-sulphide classification scheme, Au-volcanogenic massive-sulphide deposits are commonly thought to be hybrid systems between volcanogenic massive-sulphide and epithermal Au deposits in bimodal felsic (or bimodal mafic in the case of the Ming mine) settings (Galley et al., 2007). Furthermore, the lithological characteristics may control or influence the fluid flow pathways, and hence the morphology, deposit growth process, and proximal discordant and regional semiconformable alteration assemblages and extents (Gibson et al., 1999). Therefore, stratigraphic reconstructions of a well preserved volcanogenic massive-sulphide deposit such as Ming may provide insight on the magmatic evolution of the host volcanic complex and the relative timing of hydrothermal events.

The Ming deposit in north-central Newfoundland contains high Au and Cu contents, and with locally high Ag and Zn. The Ming deposit is currently being mined and has reserves (diluted and recovered) of 1.50 Mt grading 1.71 weight per cent Cu, 0.36 weight per cent Zn, 9.15 g/t Ag, and 2.06 g/t Au, and combined measured and indicated resources of 2.47 Mt grading 2.27 weight per cent Cu, 0.44 weight per cent Zn, 9.08 g/t Ag, and 2.15 g/t Au. The deposit comprises four discrete, elongated Cu-Au-(Zn-Ag) massive to semi-massive (<50 volume per cent) sulphide lenses, all plunging 30–35° to the north-northeast and spaced 30 m to 50 m apart from each other at a similar stratigraphic position. Herein the authors provide preliminary observations on stratigraphic and alteration features and discuss possible genetic relationships between the host rocks and the genesis of synvolcanic, precious metal–rich sulphide lenses at the Ming mine.

GEOLOGICAL SETTING

The Ming mine is located in the Baie Verte Peninsula (Fig. 1) in north-central Newfoundland. These rocks straddle the boundary between the Humber Zone to the west and a series of ophiolitic slivers and enclaves to the east in a narrow, fault-bounded belt, situated between the Baie Verte Brompton Line and the Green Bay Fault (Hibbard, 1983). The ophiolite units comprise mainly suprasubduction-zone rocks of mafic to ultramafic composition, including boninite (van Staal and Barr, 2012). These include the ca. 490 Ma (Dunning and Krogh, 1985; Cawood et al., 1996; Skulski et al., 2010) Advocate Complex (Burnshall, 1975), the Pointe Rousse Complex (Norman and Strong, 1975), the Betts Cove Complex (Bédard et al., 1998; Bédard, 1999), and rocks within the southern Pacquet Harbour Group (Hibbard, 1983; Piercey et al., 1997). Collectively, the ophiolite units form the Baie Verte Oceanic Tract ("BVOT"; van Staal (2007)) and basement to the disconformably overlying volcano-sedimentary cover sequences of the Snooks Arm Group (cover to the Betts Cove Complex) (Upadhyay, 1973; Jenner and Fryer, 1980; Hibbard, 1983), its equivalent upper Pacquet Harbour Group (Skulski et al., 2010), Flat Water Pond Group, and Pointe Rousse cover sequence. Several large Late Ordovician to Early Silurian granitoid plutons intrude the Baie Verte Oceanic Tract, including the ca. 446–432 Ma Burlington granodiorite, the ca. 436 Ma Cape Brulé porphyry, and the ca. 429 Ma Dunamagon granite (Fig. 2; Hibbard, 1983; Cawood et al., 1993; V. McNicoll, unpub. data, 2009).

The Ming deposit host sequence is part of the lower Pacquet Harbour Group. The base of the group consists of low-Ti boninite with minor felsic tuff and rhyodacitic flows (Fig. 2; Hibbard, 1983; Piercey et al., 1997) that are intruded by multiple generations of tholeiitic gabbro dykes that may possibly be the co-genetic tholeiitic feeders to units higher in the lower Pacquet Harbour Group (Piercey et al., 1997). This is overlain by a 2.5 km wide (Skulski et al., 2010) sequence of quartz-pyric, rhyodacite, felsic tuff, and tuff breccia herein referred to as the Rambler rhyolite. The Ming deposit is hosted in the Rambler rhyolite, in the uppermost part of the lower Pacquet Harbour Group (Fig. 2)

The ore consists of chalcopyrite, pyrite, sphalerite, pyrrhotite, minor galena, and trace electrum (Au-Ag alloy). The sulphide lenses are spatially associated with several zones of metamorphosed, hydrothermally altered footwall rocks.

Metamorphism in the lower Pacquet Harbour Group does not exceed upper greenschist facies, except near the Ordovician-Silurian intrusive bodies where contact metamorphism locally reaches the amphibolite facies (Tuach and Kennedy, 1978). The regional structural evolution of the peninsula has recently been examined by Castonguay et al. (2009 and references therein), and re-evaluated by Skulski et al. (2010). The Ming mine area was affected by at least three phases of regional deformation. D_1 resulted from the obduction of the Baie Verte Oceanic Tract and is poorly developed east of the Baie Verte Brompton Line (Skulski et al., 2010). D_2 is defined by an east-striking cleavage to a penetrative schistosity (S_2) that is axial-planar to megascopic east-trending,

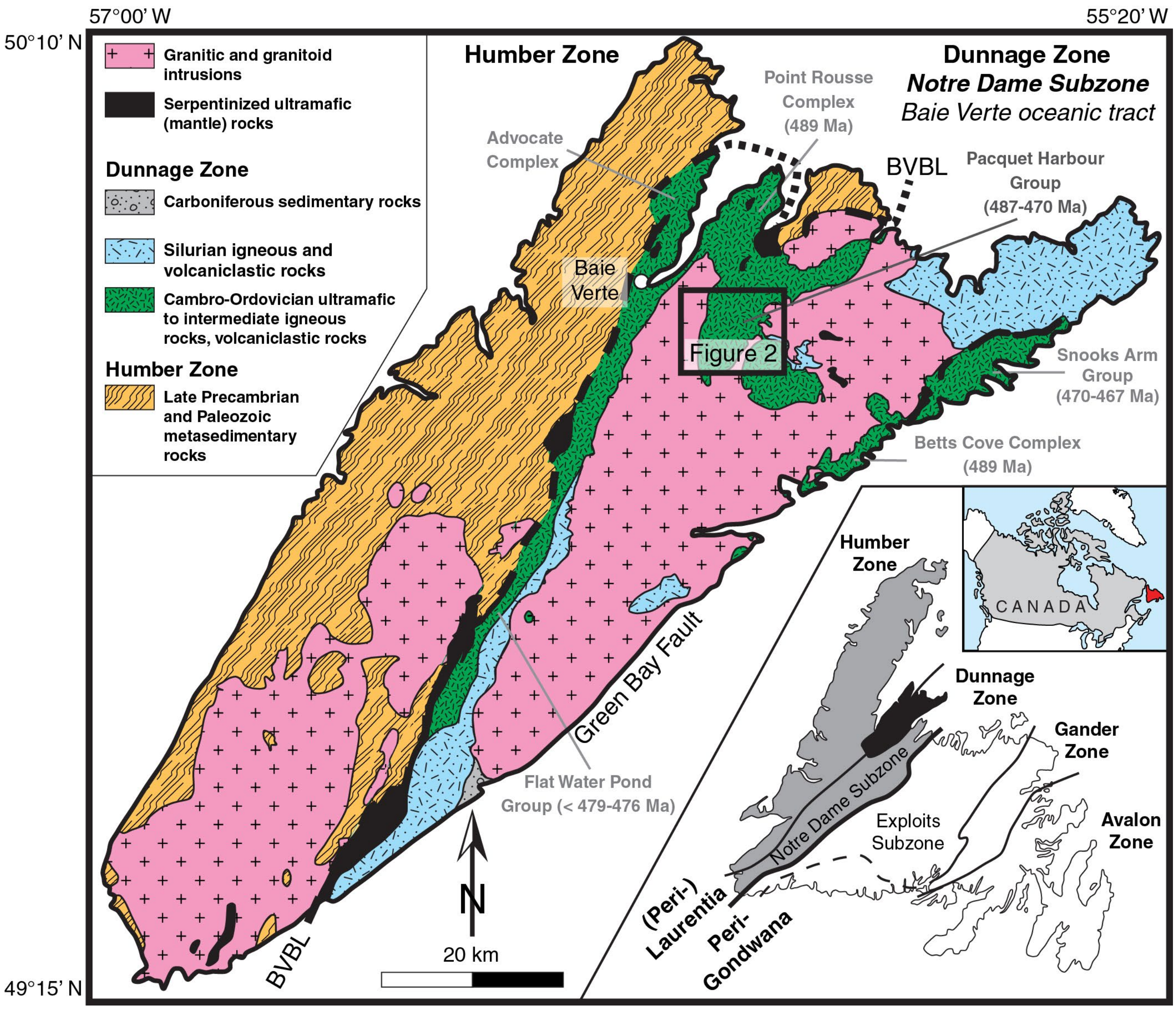

Figure 1. Simplified geological map of the Baie Verte Peninsula (modified from Skulski et al., 2010, and references therein) with the (peri-)Laurentian (inset: in grey) and (peri-)Gondwanan tectonostratigraphic zones forming the Appalachian orogenic belt in Newfoundland (Williams, 1979). BVBL = Baie Verte-Brompton Line.

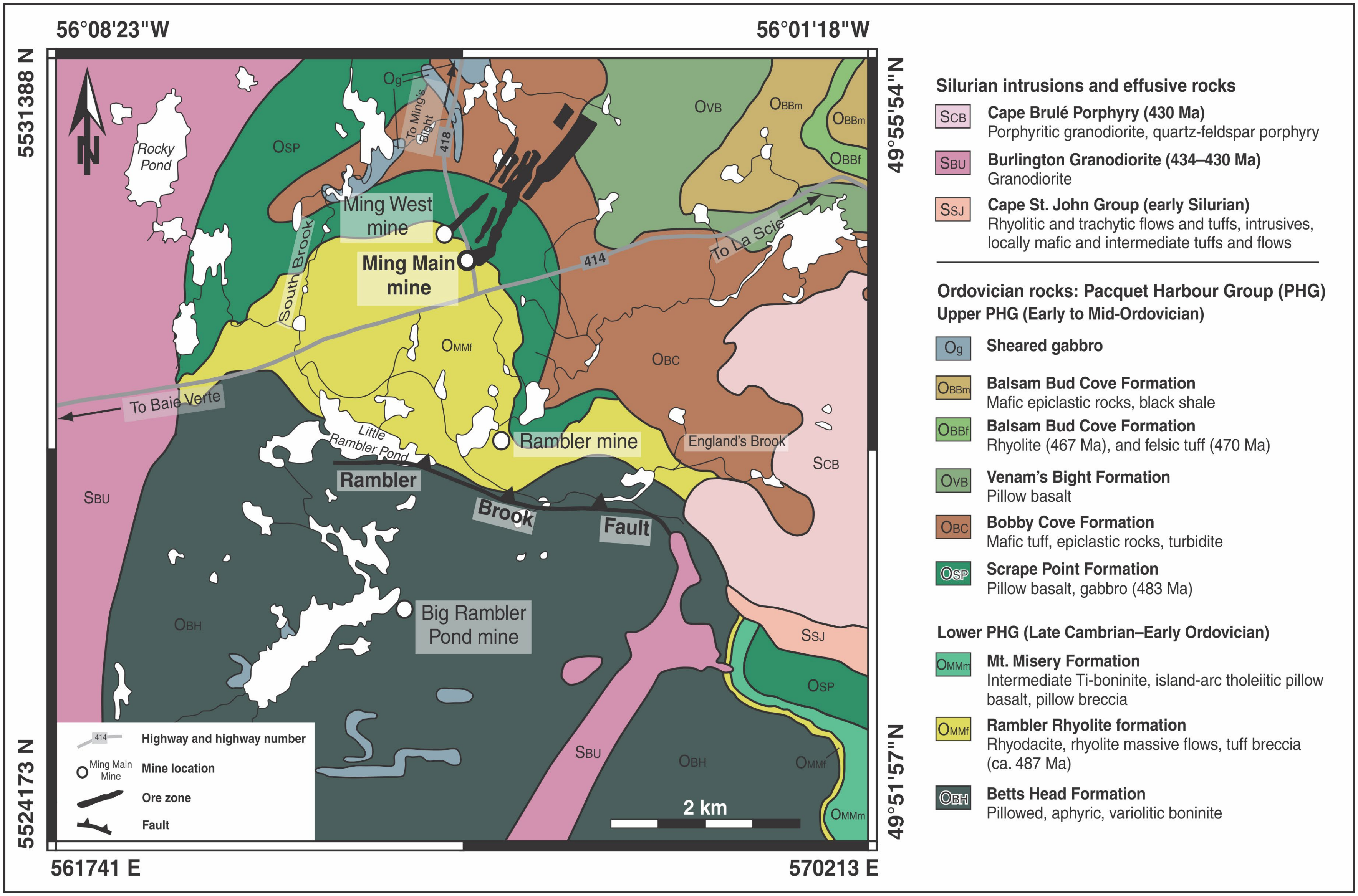

Figure 2. Regional geology map of the study area, Baie Verte Peninsula with Ming volcanogenic massive-sulphide orebodies projected to surface and shown in black. Both datums are shown in WGS 84 (top and right) and UTM 21N NAD 83 (bottom and left). Map modified from Pilgrim (L. Pilgrim, Rambler Metals and Mining Canada Ltd., unpub. technical report, 2009), Tuach and Kennedy (1978), Castonguay et al. (2009), and Hibbard (1983). Ages are from Castonguay et al. (2009) and Cawood et al. (1993).

open to tight F_2 folds. The S_2 fabric is locally associated with a strong L>S fabric. The north-dipping south-directed Rambler Brook Fault, south of the Rambler rhyolite is interpreted as a D_2 structure. D_3 is characterized by open, upright cross folds with axial planes trending north-northeast (Fig. 2). The elongated shape of the orebodies (Fig. 2, 3) is in large part due to the S_2 stretching and superimposed effect of D_3 deformation (Castonguay et al., 2009). The extent to which the deformation has affected the architecture and metal distribution of the Ming deposit remains unconstrained and is currently under study (Brueckner et al., 2014).

ORE LENSES AND HOST UNITS

Detailed mapping was undertaken northwest of the deposit in different underground levels (329, 434, and 444) along the 1807 zone. The mapping is complementary to the work by Pilote and Piercey (2013). Moreover, a total of 23 surface and underground drillholes (16 from the Ming South down plunge) were logged in an attempt to establish a stratigraphic correlation and identify the different units hosting and overlying the deposit. Rocks underlying the massive-sulphide deposits are hydrothermally altered and regionally metamorphosed; thus, in most cases obliterating the primary mineralogy of the rocks. Rock types are therefore identified based on the texture, presence of relict phenocrysts, secondary mineralogy, and geochemistry. Nomenclature used for volcanic and volcaniclastic rock classification is as published in White and Houghton (2006). Least altered volcanic and volcaniclastic rocks (i.e. SiO_2>66 weight per cent and Na_2O = 2–5 weight per cent), although deemed felsic, have intermediate compositions based on immobile trace-element ratios (e.g. Zr/TiO_2<0.07) (J.-L. Pilote, unpub. data, 2014).

1807 zone

Based on underground mapping on several levels in the 1807 zone of the deposit, the stratigraphic footwall unit to the massive-sulphide deposits on level 329 (Fig. 4) is a dark purple to olive-green felsic lapilli tuff (Fig. 5a) with quartz porphyroclasts making up to 15 volume per cent of the rock. The lapilli-sized fragments, which make up 30 volume per cent of the rock, are lighter in colour and are subangular and elongated parallel to the main lineation. This fragmental unit is in sharp contact with a lower unit composed predominantly of a dark purple, coherent, equigranular to quartz-phyric rhyodacite that contains up to 15 volume per cent quartz. Down plunge of the 1807 zone, rocks on levels 434 and 444 are similar to those present on level 329; however, there are significant differences in the distribution and size of fragments, indicating lateral volcanic facies changes. On levels 434 and 444, stratigraphically underlying the massive sulphide is a 3 m thick unit of dark purple-grey, biotite-rich felsic lapilli tuff with bombs comprising 10% of the rock. The bombs are dark pink-purple, quartz-phyric (approximately 5–10 volume per cent), and vary from 2 cm

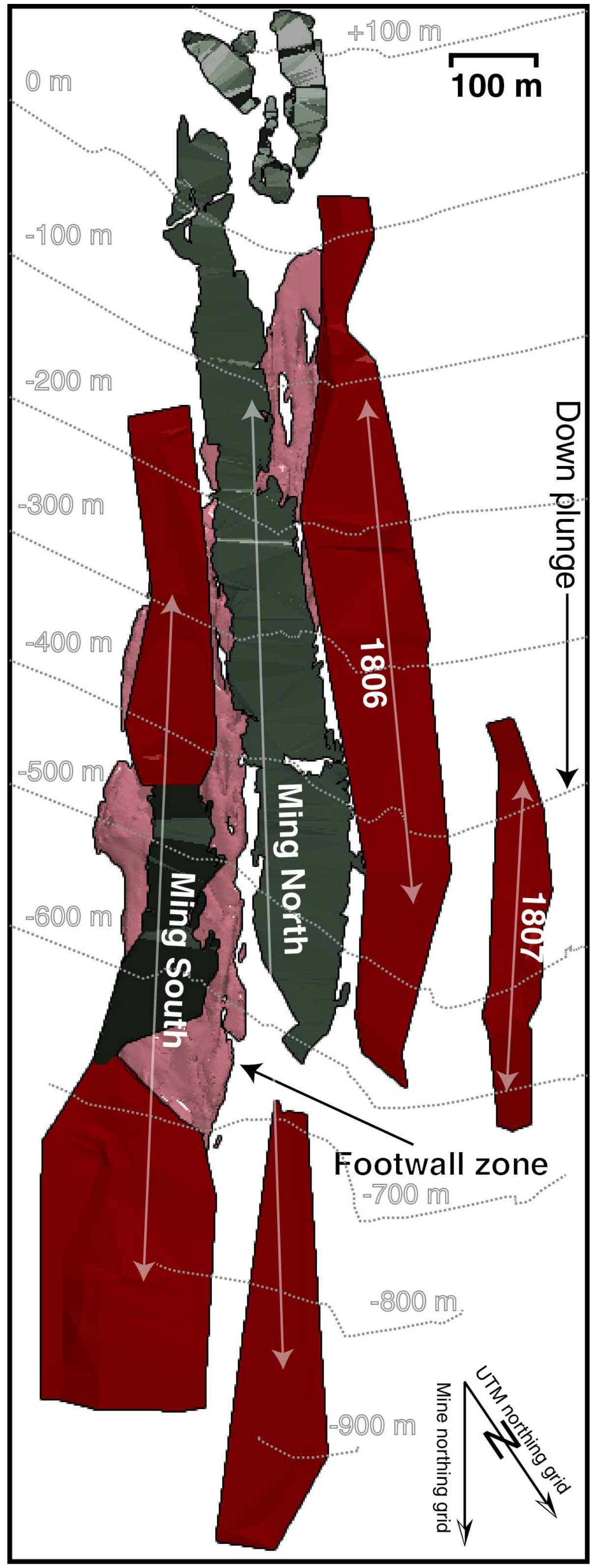

Figure 3. Plan view of 3-D model of Ming orebodies projected to surface (0 m). The surface of wireframes in red represent orebodies currently in production or those that will be mined, whereas those in grey are previously mined orebodies. Mine north is 34° east of UTM north. Model modified from Pilgrim (L. Pilgrim, Rambler Metals and Mining Canada Ltd., unpub. technical report, 2009).

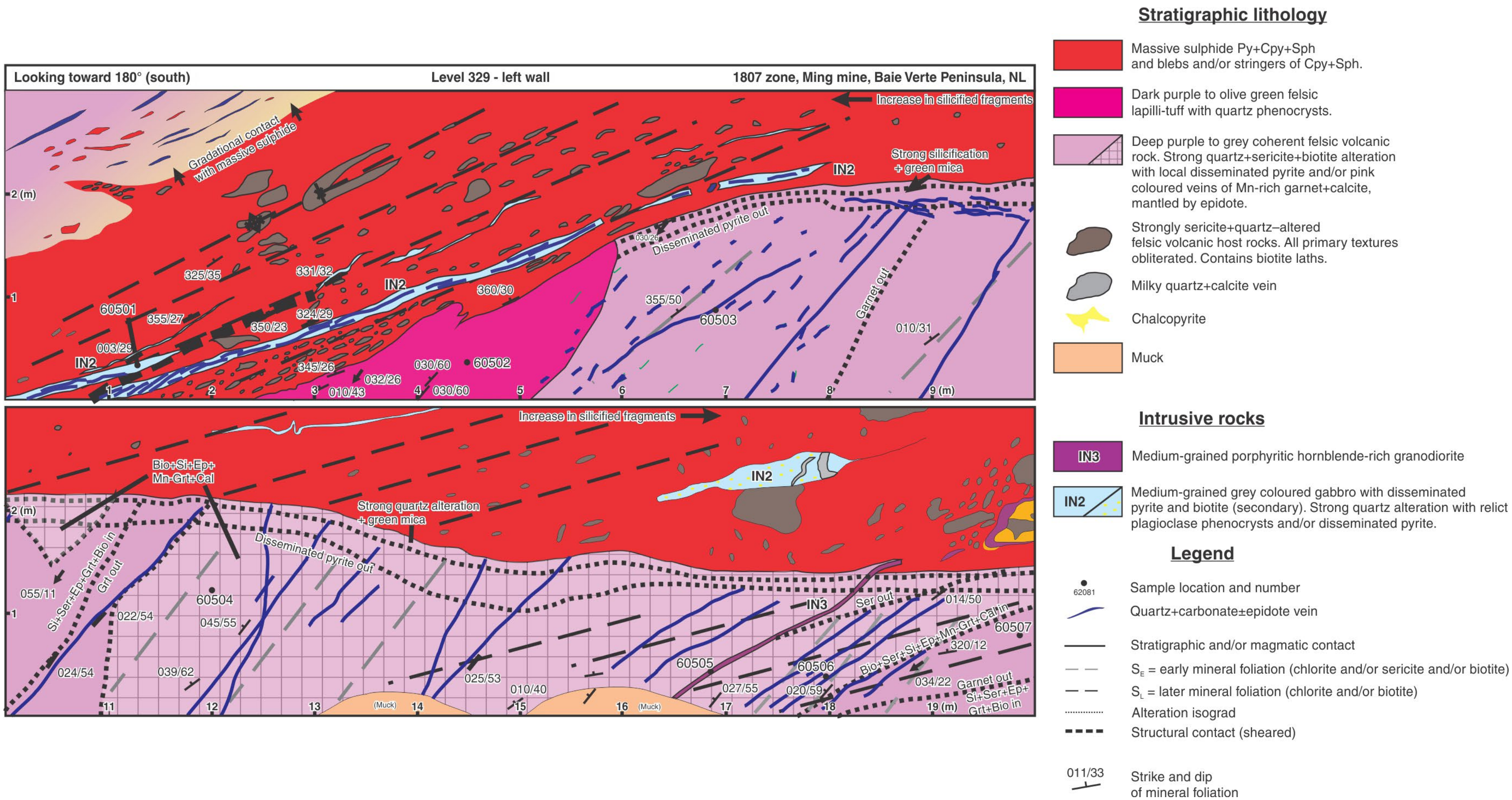

Figure 4. Schematic cross-section of the back wall in level 329, 1807 zone showing the relationship between the different lithological units, including the massive-sulphide horizon where it is intruded by IN2 and IN3 dykes; Bio = biotite, Si = silica, Ep = epidote, Mn = manganese, Grt = garnet, Cal = calcite, Ser = sericite, Py = pyrite, Cpy = chalcopyrite, Sph = sphalerite.

to 30 cm in length (length to width ratio of 3:1). This unit has a minimum thickness of approximately 3 m. This unit is in gradational contact with the lower coherent felsic volcanic unit and the transition from a lapilli tuff to coherent felsic volcanic rocks occurs over a stratigraphic interval of 10 m from the underlying massive-sulphide deposits.

The massive-sulphide body is stratiform to locally discordant to the host volcanic rocks and has a maximum thickness of about 4 m. The massive-sulphide deposits are composed of pyrite and chalcopyrite with trace amounts of sphalerite that forms clots that are less than 2 cm in diameter. Quartz dominates (<20 volume per cent) the gangue mineralogy, is interstitial to the sulphide minerals, and occurs throughout the lens. In the southeast part of the lens, on levels 434 and 434, centimetre-scale layers of chalcopyrite are gradually replaced by centimetre-scale layers of sphalerite toward the northwest. The massive sulphide contains up to 20 volume per cent of strongly quartz- to sericite-altered felsic volcanic clasts as shown on level 329 (Fig. 4). The clasts are elongated and folded due to deformation and cut by a foliated porphyritic hornblende-rich granodiorite (IN3; Fig. 4), setting a maximum age (predate main deformation) relationship for their incorporation into the lens.

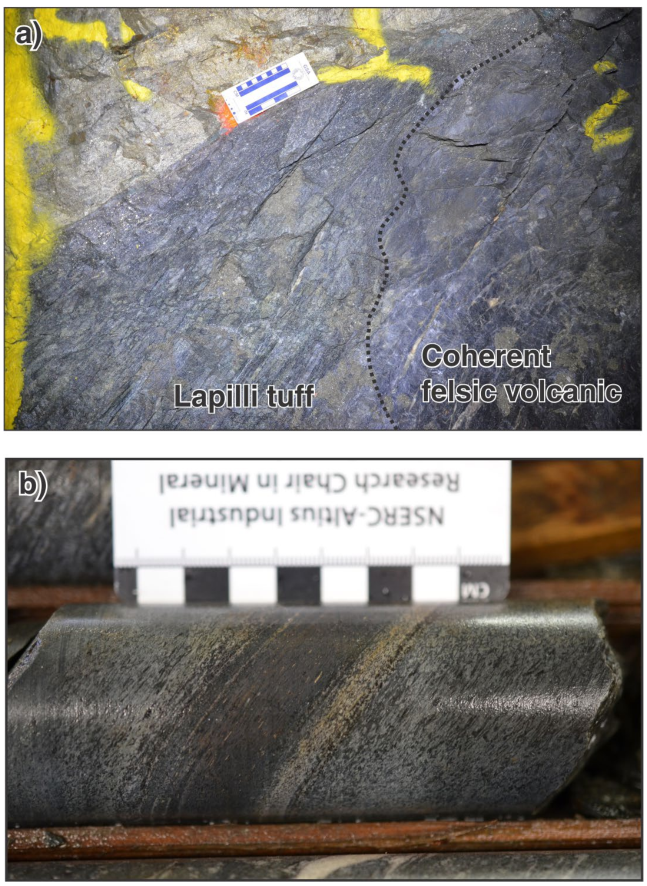

Figure 5. Photographs of an underground exposure and a drill-core section. **a)** View looking south in level 329 of the contact between the medium-grained, light green, quartz-phyric crystal lithic lapilli tuff and the deep purple coherent felsic volcanic units underlying the massive sulphide; 2014-180. **b)** Representative sample of the magnetite-pyrite-rich layer intercalated with a fine- to medium-grained volcanogenic sedimentary rock (predominantly siltstone) (DDH RM07-20 m; 635 m downhole); 2014-181. Photographs by J.-L. Pilote.

Stratigraphically overlying the massive-sulphide lens is an up to 12 m thick unit of light white-grey to dark grey polymictic felsic quartz-phyric crystal lithic lapilli tuff that fines upward. This hanging-wall fragmental unit contains irregularly shaped pyrite-rich pods that are elongate parallel to S_2, a feature also present on level 375 (Pilote and Piercey, 2013). This unit is overlain by a dark grey to reddish-grey magnetite-rich siltstone (Fig. 5b). The siltstone comprises numerous synsedimentary layers of magnetite 3 cm or less thick. This sedimentary unit has a sharp upper contact in which it contains coarse-grained, rosette-shaped porphyroblasts of hornblende along a preferred structural plane (garbenschiefer texture). This unit occurs throughout the deposit and constitutes a marker horizon at the base of the upper Pacquet Harbour Group, indicating a hiatus in volcanism.

Ming South down plunge

The Ming South down plunge is the deepest and easternmost known orebody of the Ming deposit (Fig. 3) and contains combined measured and indicated resources of 1.11 Mt grading 1.64 weight per cent Cu, 0.57 weight per cent Zn, 9.94 g/t Ag, and 2.24 g/t Au (L. Pilgrim, Rambler Metals and Mining Canada Ltd., Technical Report, 2009). The zone is not currently being mined and there is no underground access; however, information was obtained from diamond-drill cores. The footwall of the Ming South down plunge is characterized by three main units (Fig. 6) to a maximum available drill-core depth of approximately 270 m below the ore horizon. It also intersects the Cu-rich lower footwall zone (*see below*).

The lowermost unit has a minimum thickness of 175 m and is a medium to dark grey, fine-grained coherent felsic quartz-phyric tuff (or possibly flow) with quartz porphyroclasts up to 1–3 mm in diameter. It is overlain by a felsic volcaniclastic succession consisting predominantly of crystal tuff to crystal lithic lapilli tuff. The rock contains up to 10 volume per cent, 2–5 mm wide white to bluish quartz phenocrysts. It is cut by chalcopyrite, pyrite, and pyrrhotite stringer veins that constitute 10–15 volume per cent of the rock. This unit is overlain by two stratabound and stratiform massive-sulphide lenses. The lower lens is comprised mainly of massive chalcopyrite, pyrite, and minor sphalerite, and elongated quartz-phyric rhyodacite clasts, whereas the upper lens is comprised of granular pyrite, chalcopyrite, and minor sphalerite and interstitial quartz. It also contains silicified felsic volcanic clasts (<10 cm in diameter) with green mica of possibly fuchsitic composition;

the green mica constitutes less than 1 volume per cent of the rock. A clear mineralogical distinction exists between the two lenses, and this is also reflected in their different metal abundances (Fig. 7), with significantly higher Cu and Au grades in the lower lens.

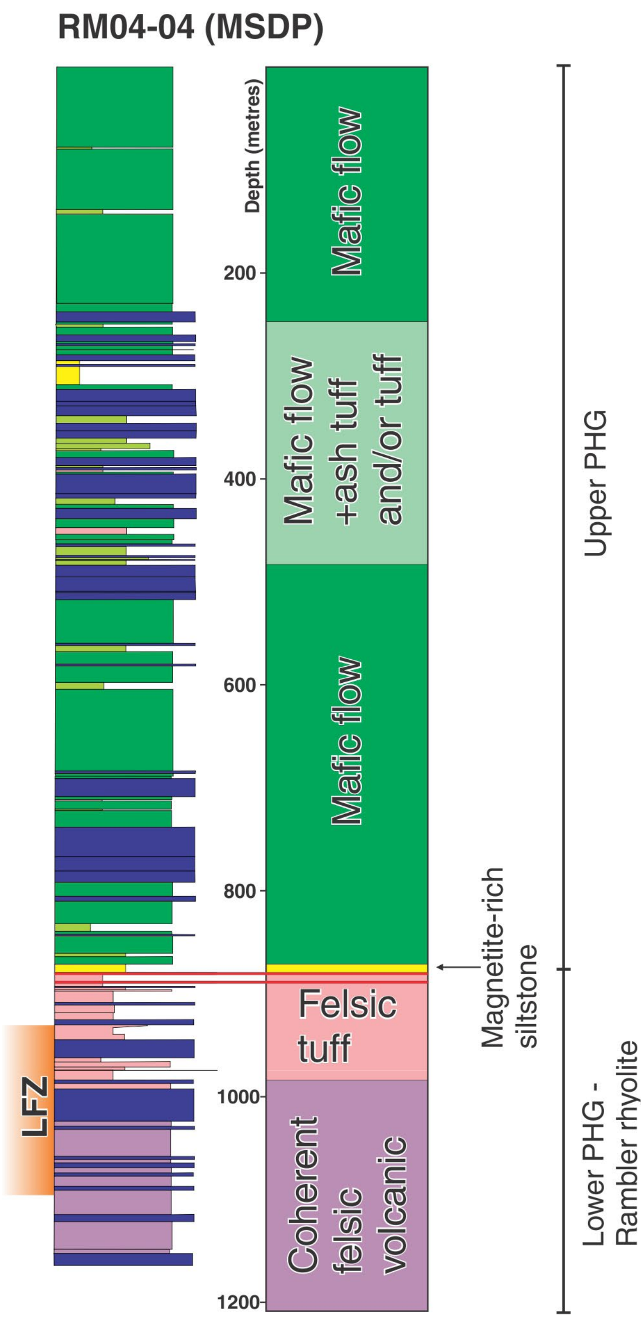

Figure 6. Representative stratigraphic section of the Ming South down plunge (MSDP). The red lines represent the two massive-sulphide lenses, underlain by two units of felsic tuff and coherent felsic volcanic rocks (Rambler rhyolite). The massive sulphide is overlain by a magnetite-rich siltstone, which in turn is overlain by mafic flows and ash-tuff rocks (upper Pacquet Harbour Group). Blue units represent undifferentiated mafic dykes. The lower footwall zone (LFZ) represents the Cu-rich stockwork underlying part of the Ming deposit. PHG = Pacquet Harbour Group

The two Ming South down plunge lenses are separated by three discrete beds (of a total maximum thickness of 10 m) of felsic tuff (Fig. 8). The lowermost bed is a medium to dark grey medium-grained quartz-phyric crystal tuff (Fig. 8a); quartz grains are white to bluish . The middle bed is a light grey to white quartz-phyric crystal tuff (Fig. 8b). The quartz crystals in that bed vary in size (2–5 mm in diameter) and are elongated parallel to S_2, which is cut by chalcopyrite-pyrite-quartz stringer veins. The uppermost bed is enclosed within the upper massive-sulphide lens and is a medium reddish-grey, felsic quartz-phyric crystal tuff (Fig. 8c). This bed contains pyrite-quartz stringer veins (<5 mm in thickness) that constitute less than 2 volume per cent of the rock. A correlation is possible among the different drillholes (Fig. 8) intersecting the upper part of the Ming South down plunge, which reaches a maximum thickness of about 11 m in its central part (RM06-04e). Although the massive-sulphide deposits and/or host tuffaceous facies are cut by, or intercalated with mafic intrusions in some areas, the approximately100 m along-strike stratigraphic continuity of the Ming South down plunge suggests a syngenetic style of mineralization.

Intrusive rocks

Pilote and Piercey (2013) documented the presence of three distinct generations of dykes and sills in the Ming deposit host succession; further information about those intrusive rocks is given here. The first generation (IN1) is a coarse-grained equigranular clinopyroxene gabbro. The clinopyroxene is commonly replaced (pseudomorphed) by chlorite. The contact with the host felsic volcanic rocks is irregular and is locally truncated by sulphide minerals due to deformation, with no evidence of intruding the latter. The coarse-grained gabbro is intruded by a fine-grained diorite

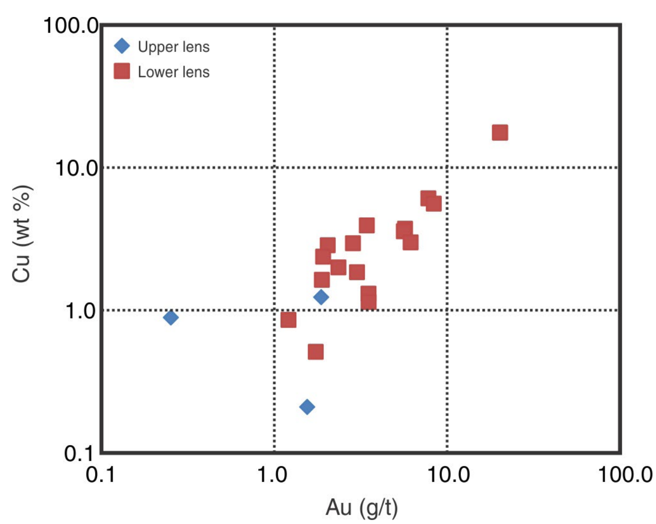

Figure 7. Historical Cu (weight per cent) and Au (g/t) grades from diamond-drill holes intersecting the two massive-sulphide lenses in the Ming South down plunge. Grades are for 1 m long assay intervals.

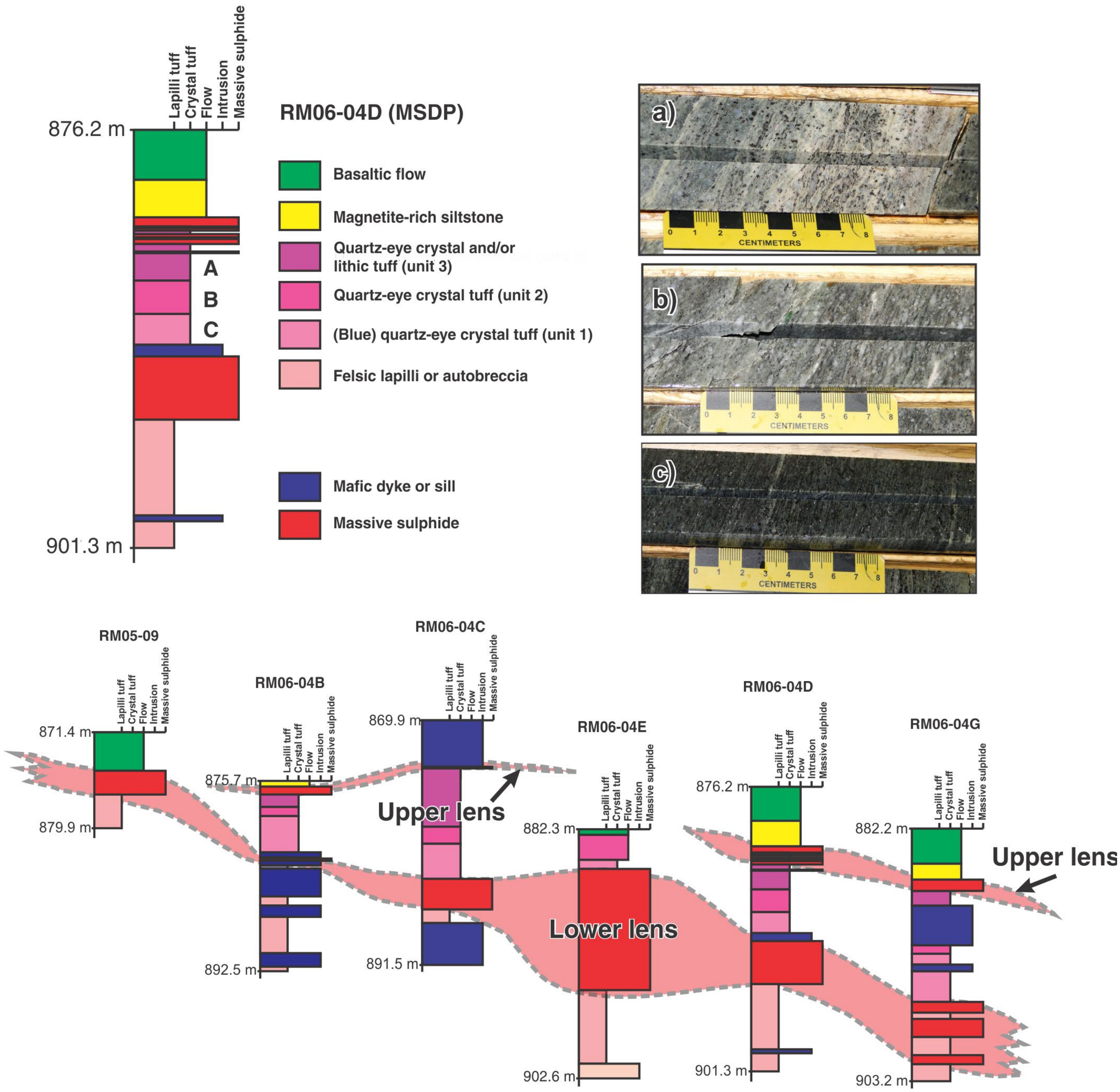

Figure 8. Graphic logs for representative diamond-drill holes intersecting the Ming South down plunge (MSDP) massive-sulphide lenses arranged in a schematic cross-section, with representative drill-core photographs of the different tuffaceous facies separating the massive-sulphide lenses; **a)** quartz-phyric crystal- and/or lithic tuff; 2014-177; **b)** quartz-phyric crystal tuff; 2014-182; and **c)** melanocratic blue quartz–phyric crystal tuff; 2014-173. The relative horizontal positions of the drillholes are not to scale. Photographs by S. Brueckner.

(IN2) that intrudes massive sulphide where it is boudinaged, dismembered, and folded. The last generation of dykes (IN3) is a porphyritic hornblende-rich granodiorite that intrudes both IN2 and the massive-sulphide minerals (*see* Fig. 7d *in* Pilote and Piercey, 2013), and is similarly deformed when cutting the latter. Preliminary lithogeochemical data indicates significant geochemical differences between each generation of dykes (Fig. 9) with the first generation (IN1) having a flat rare-earth element (REE) pattern, whereas IN2 and IN3 are progressively more evolved with slight to moderate light-REE enrichment, respectively.

HYDROTHERMAL ALTERATION

The different hydrothermal alteration assemblages present at the Ming mine were characterized by core logging, underground mapping, petrographic microscopy, and scanning electron microscopy–energy dispersion X-ray imaging (SEM-EDX) at Memorial University. Whole-rock lithogeochemical analysis and visible to near infrared–shortwave infrared spectrometry (VNIR-SWIR) have also been done, but results and data analysis are pending and will therefore be discussed in a later publication. Alteration mineral assemblages vary among the deposit and with depth and will be discussed in terms of their mineralogical assemblages.

A sericite (muscovite)-green mica-quartz±chlorite±epidote±magnetite±sulphide mineral (herein referred to as sericitic) alteration assemblage is ubiquitous in the deposit host succession, interpreted as resulting from rock interaction with a low-temperature hydrothermal fluid (e.g. Franklin et al., 2005). This sericitic alteration, responsible for a greyish coloration in felsic rocks, underlies the 1807 and 1806 (Brueckner et al., 2014), and Ming South down plunge zones. The relative proportions of the various key minerals in this assemblage vary throughout the deposit. Chlorite and epidote are progressively more abundant at depth starting from the immediate footwall. There are no chemical analyses of the green mica available yet, but its bright green colour is distinct from all other micaceous phases in the deposit. In the 1807 and Ming South down plunge zones, the green mica forms foliation-parallel elongated pods that are less than 2 cm long and closely associated with the massive-sulphide mineralization. The green mica is widespread and abundant (>5 volume per cent) up to approximately 50 m stratigraphically below the 1806 zone (Fig. 10a) where it correlates with high Au content (Brueckner et al., 2014). Epidote, magnetite, and garnet are minor phases in this alteration assemblage. Epidote is fine- to very fine-grained, and occurs as anhedral to lath-shaped grains together with quartz. Magnetite occurs as small (<2 mm diameter) euhedral grains less than 2 mm in size. Garnet is restricted to the footwall of the 1807 zone. The grains are hypidioblastic, less than 3 mm in size, and commonly occur together with narrow (<5 mm) quartz veinlets that crosscut the foliation in the host rocks and the massive-sulphide mineralization (Fig. 10b). Stringer veins of pyrite-chalcopyrite-pyrrhotite comprise up to 50 volume per cent of the host rock in the sericite-altered footwall units. The semimassive sulphide mineralization consists of anastomosed stringer veins and veinlets that crosscut the host rocks (Fig. 10c).

Fifty to one hundred metres stratigraphically below the Ming South and Ming North zones, the footwall consists of a coherent dark-bluish quartz-phyric volcanic rock that is overprinted by a hydrothermal alteration assemblage of chlorite-quartz-epidote-chalcopyrite-pyrrhotite-pyrite±apatite±sphalerite±Bi-telluride minerals. This rock only occurs below the Ming South and Ming North zones. A sample collected from below the Ming North orebody at the 1450 level (~440 m below surface), shows an intergrowth relationship between quartz, chalcopyrite, pyrrhotite, and epidote forming stringer veins (Fig. 10d). The stringer veins are partly transposed into the dominant foliation and range from a few millimetres to up to 10 cm in thickness. The dark bluish coloration of the rock results from the high abundance of Fe-rich chlorite; this mineral typically

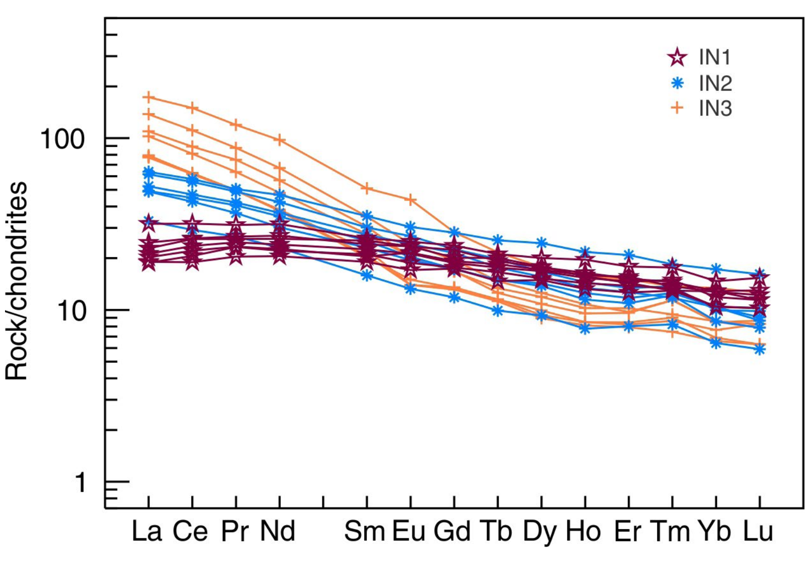

Figure 9. Chondrite normalized rare-earth–element plots for samples from mafic to intermediate dykes (IN1, IN2, and IN3) in this study. Chondrite-normalizing values are from Sun and McDonough (1989).

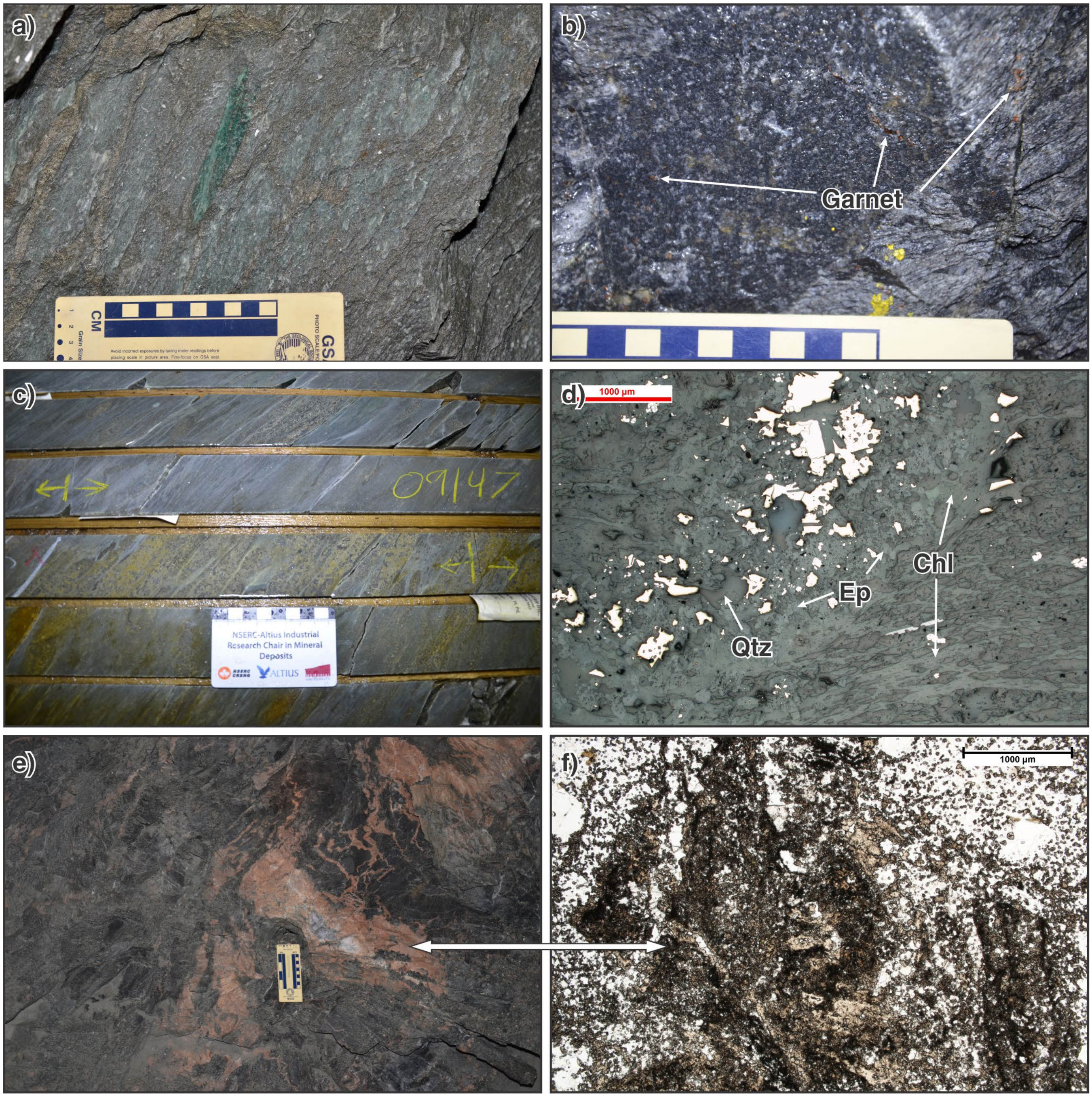

Figure 10. Representative and selected underground and drill-core photographs and photomicrographs of the different alteration styles characterizing the Ming footwall rocks. **a)** A coherent felsic volcanic rock is altered to sericite (with green mica) and sulphide mineralization oriented parallel to foliation (level 107, 1806 zone); scale is in centimetres; 2014-176. **b)** A deep purple sericite-altered coherent felsic volcanic overprinted by garnet-biotite (level 329, 1807 zone); scale is in centimetres; 2014-174. **c)** A representative drill-core section underlying the massive-sulphide lens with strong sericite+sulphide alteration (RM04-04; 219 m downhole); scale is in centimetres; 2014-171. **d)** Photomicrograph in reflected light of a strongly chlorite-altered felsic volcanic rock with coexisting chlorite (Chl), quartz (Qtz), epidote (Ep), chalcopyrite, and pyrrhotite (sample 62085; level 1450); 2014-170. **e)** View looking southwest of a Mn-altered quartz-phyric coherent felsic volcanic rock underlying the massive sulphide. The pink, light grey, white, and dark green-black rocks are Mn-garnet, quartz, calcite, and quartz-phyric felsic volcanic rock, respectively (level 481, 1807 zone); scale is in centimetres; 2014-172. **f)** Photomicrograph in transmitted light of sample 62199 (level 481, 1807 zone) showing very fine- to fine-grained quartz (clear) with dusty Mn-garnet (light to dark pink) and calcite (clear); 2014-178. Photographs by J.-L. Pilote.

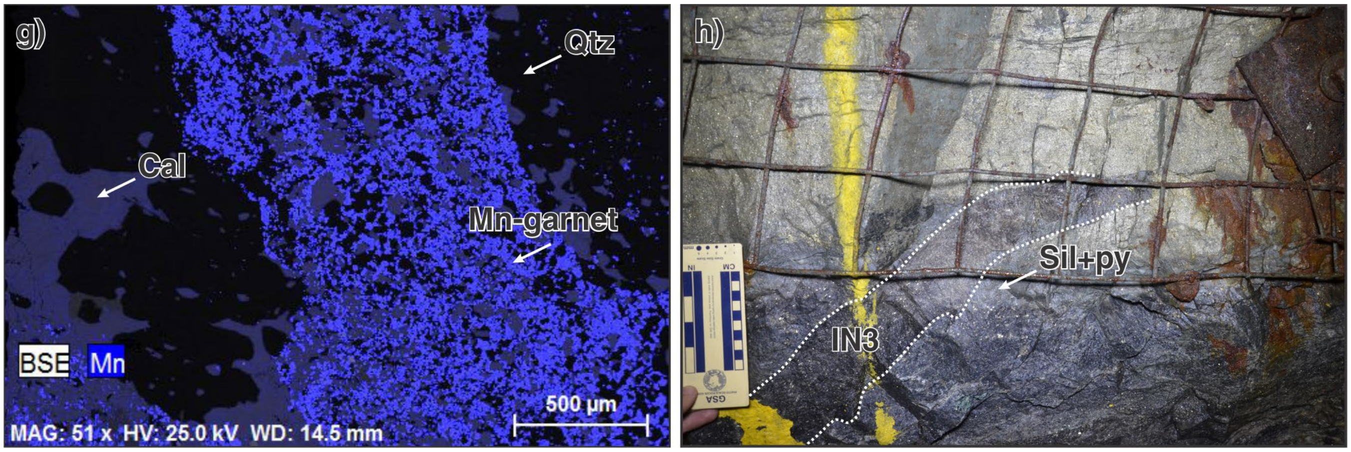

Figure 10 continued. Representative and selected underground and drill-core photographs and photomicrographs of the different alteration styles characterizing the Ming footwall rocks. **g)** Scanning electron microscopy–energy dispersion X-ray imaging image of sample 62199 (level 481, 1807 zone) showing the distribution of Mn (blue) and the relationship between calcite (Cal), quartz (Qtz), and Mn-rich garnet (Mn-garnet). Note the abundant Mn-rich inclusions in quartz in the right part of the image. 2014-175. **h)** View looking south in level 329 of the silica+pyrite alteration (sil+py) overprinting IN3 and the felsic volcanic footwall rocks; scale is in centimetres; 2014-169. Photographs by J.-L. Pilote.

occurs in the stockwork or high-temperature hydrothermal fluid upflow zone to volcanogenic massive-sulphide deposits (e.g. Lydon, 1984; Goodfellow et al., 2003). Moreover, the chlorite-altered rocks contain Bi-telluride minerals, which are also present in the 1806 zone (Brueckner et al., 2014); this mineral generally occurs in Au-rich volcanogenic massive sulphide, epithermal, porphyry Au (± Cu), and Au-skarn deposits (Cook et al., 2009 and references therein) and is considered to reflect input of magmatic fluids and/or volatile gases to the hydrothermal system (e.g. Huston, 2000; Dubé et al., 2007a, b).

The 1807 zone is characterized by greyish to salmon-pink alteration, also within the sericitic zone described above, that consists of veins and veinlets (5 mm up to 20 cm in thickness) that crosscut (and have brecciated, in some areas) the volcanic rocks. This alteration seems to be restricted to the 1807 zone and its proximal footwall (extends approximately 10 m below the sulphide mineralization). The veins and veinlets are composed of quartz-garnet-carbonate minerals that are transposed and folded in the foliation (Fig. 10e). Scanning electron microscope–energy-dispersive X-ray spectroscopy illustrates that the material consists of fine-grained quartz with a dusty matrix of very fine-grained Mn-Ca-Fe spessartine-almandine and Mn-rich calcite (Fig. 10f). Element distribution maps of this alteration show Mn-rich minerals disseminated throughout the volcanic rock fragments (Fig. 10g) that could suggest a Mn diffusive exchange with the hydrothermal alteration fluids (Ganguly, 2002). Despite the latter, fragments have retained most of their sericitic mineral assemblages. All generations of mafic dykes crosscut this Mn alteration and the presence of a Mn-altered felsic tuff xenolith within a dyke of granodiorite belonging to the latest generation (IN3) provides some temporal constraints for Mn introduction in the Ming mine system.

Quartz-pyrite alteration is locally present in the deposit and is stratigraphically immediately below and above the massive-sulphide mineralization throughout the Ming deposit. The intensely quartz-altered zone extends 20–30 cm within the immediate footwall and hanging-wall rocks and also contains cubic pyrite porphyroblasts up to 1 m below and above massive-sulphide mineralization. The pyrite grains are stretched into the dominant lineation (~030°N). Both quartz and pyrite overprint IN3 dykes (Fig. 10h), and this indicates that this alteration assemblage postdates the intrusive phase and may be syndeformation. Samples from immediately above the massive-sulphide mineralization in the Ming South down plunge and 1806 zones have SiO_2>88 weight per cent with Na_2O <0.11 weight per cent (n = 4; J.-P. Pilote, unpub. data, 2014), reflecting the intense silicification (and/or leaching of other elements) of the rock.

DISCUSSION AND SUMMARY

The footwall succession at the Ming mine consists predominantly of a coherent volcanic rock of intermediate to felsic composition. The relative abundance of fragmental facies gradually increases upstratigraphy (Fig. 6). The massive to volcaniclastic transition may reflect the evolution from a subaqueous intermediate to felsic flow-dome complex to an eruptive volcaniclastic succession. It has been suggested by Gibson et al. (1999) that the morphology of massive-sulphide deposits is controlled primarily by the facies architecture of the host volcanic rocks (i.e. flows and/or dome complex versus volcaniclastic rocks). A flow-dominated succession, such as the Rambler rhyolite at Ming, may have inhibited diffusion and mixing of ascending hydrothermal fluids as opposed to volcaniclastic rocks that are much more permeable. The localization of mineralization in volcaniclastic rocks (but proximal to the flow and/or domes), suggests that the fluids were likely focused along permeability contrast boundaries between the coherent and volcaniclastic rocks. It is possible that these boundaries are synvolcanic structures that focused the circulating hydrothermal fluids, resulting in the development of a lens-shaped massive-sulphide deposit above a stringer vein or stockwork zone. Based on the spatial distributions of the lower footwall zone (i.e. subparallel to the Ming South down plunge and Ming North lenses; Fig. 3) and the intense chlorite alteration and chalcopyrite-pyrrhotite-rich sulphide assemblages, it is likely that this zone represents high-temperature hydrothermal fluid discharge along a synvolcanic structure. The elongated shape of the massive-sulphide zones at Ming mine is the result of multiphase deformation (interference between D_1 and D_2: Tuach and Kennedy (1978); Hibbard (1983); Brueckner et al. (2014)); however, the current en échelon distribution of the lenses is likely due to the development of a set of synvolcanic faults and related secondary splays in an extensional setting. The primary architecture of the volcanic complex hosting the Ming ore lenses and its effects on the distribution and style of alteration and associated ore zones will be determined through detailed stratigraphic reconstruction as part of the current project.

The results herein suggest that the chloritic alteration in the Ming South down plunge and Ming North ore bodies represent high-temperature hydrothermal alteration (>300°C; e.g. Lydon (1988); Ohmoto (1996)). In contrast, the sericite-dominated alteration in the 1806 and 1807 zones is more consistent with these zones forming from lower temperature hydrothermal fluids (e.g. Lydon, 1988; Brueckner et al., 2014). In both the chloritic and sericitic alteration zones at Ming there are also ubiquitous biotite porphyroblasts that overprint the chloritic and sericitic alteration assemblages and formed as an upper greenschist metamorphic overprint of the hydrothermally altered rocks (Barrett and MacLean, 1994).

Manganese enrichment is locally important at Ming mine, as evidenced by the enrichment of Mn in garnet and calcite below the 1807 zone. Although it has not yet been determined, the origin of the Mn enrichment at the Ming deposit may be similar to that observed in other volcanogenic massive-sulphide deposits, notably at LaRonde Penna and Bousquet 2-Dumagami in the Abitibi greenstone belt. Dubé et al. (2007b; 2014) documented a Mn alteration characterized by transposed millimetre-wide bands of Mn-rich Fe-Ca spessartine or almandine-epidote-clinozoïsite-muscovite-pyrite±pyrrhotite in the footwall rocks. Dubé et al. (2007b) proposed that the Mn enrichment of the garnet crystals results from the replacement and leaching of manganiferous iron carbonate from the surrounding rocks, which is locally present as disseminations below one of the auriferous orebodies (i.e. 20 North lens), followed by metamorphism of Mn-enriched chloritic zones and concentration of Mn within garnet and other aluminous phases. Although preliminary at this point, further mineralogical and geochemical investigations will shed light on the source(s) and process(es) causing this Mn enrichment at the Ming deposit. Moreover, this assemblage of alteration has economic implications at LaRonde where Mn-rich zones are commonly spatially associated with auriferous massive-sulphide deposits (Dubé et al., 2007b).

Quartz alteration (silicification) is important in some zones of the Ming deposit. In the 1806, 1807, and Ming South down plunge zones, the intensely silicified (±pyrite) horizon immediately overlying and underlying the massive-sulphide deposits was previously thought to have formed as a result of hydrothermal leaching, and this semipermeable siliceous cap then permitted sulphide deposition below the seafloor (Pilote and Piercey, 2013). This interpretation was based on the presence of elongated, centimetre-scale sulphide lenses in the hanging wall that indicated prolonged hydrothermal circulation and replacement of the felsic volcaniclastic rocks; however, Brueckner et al. (2014) argued that the silicification occurred during the waxing and peak of the hydrothermal activity together with the deposition of precious metal-bearing phases. The recent discovery of the silica-pyrite alteration assemblage overprinting IN2 dykes, however, indicates that it formed long after volcanogenic massive-sulphide deposition and may be the result of silica mobilization from the massive-sulphide deposits into the immediately adjacent wall rocks during metamorphism and/or deformation.

In addition to synvolcanic faulting, the geometry of the various lenses in the Ming deposit is largely controlled by deformation, which is especially true for the 1807 zone that exhibits evidence of centimetre- to orebody-scale mechanical remobilization of the massive-sulphide minerals (e.g. massive-sulphide minerals piercing in the host rocks). A mafic dyke (IN2) intruding the massive-sulphide deposits on level 434 records multiple generations of chalcopyrite veinlets oriented parallel with the structural fabrics (Fig. 11). The massive-sulphide deposits in the northern part of the 1807 lens show distinct characteristics compared to its southern counterpart (Fig. 12). The former has higher Cu-Au contents coexisting with thin layers of sphalerite and also contains less silicified volcanic host-rock fragments in the massive-sulphide deposits than the latter. Preliminary structural analyses show a structural relationship between a late northeast fabric (S_3 of Castonguay et al., 2009) and the orientation of the massive-sulphide lens. These features provide evidence for local remobilization of metals attendant with deformation and metamorphism, and this is the focus of ongoing work at the Ming mine as part of this research project.

Despite local mechanical remobilization of the massive-sulphide minerals in the northwesternmost part of the 1807 zone due to postmineralization deformation events (Taconic 3, Salinic, and Acadian orogenies; e.g. van Staal and Barr (2012)), evidence for a synvolcanic origin for the massive-sulphide lenses and their precious-metal enrichment include: 1) the spatial distribution of the massive-sulphide lenses and their relationship with the host rocks (i.e. stratabound and stratiform in the southern part of the 1807, 1806, and Ming South down plunge zones); 2) the presence of crosscutting high-temperature (chloritic) and lower temperature proximal (sericitic) hydrothermal alteration assemblages underlying the massive-sulphide deposits; 3) the presence of synvolcanic dykes that cut the ore; 4) the intense deformation of all ore and alteration assemblages; 5) the presence of atypical mineralogy with abundant sulphosalt minerals associated with an enrichment in the epithermal suite of elements (Au, Ag, As, Hg, Sb, Bi) that suggest a magmatic contribution to the mineralizing fluids (Brueckner et al., 2014); and 6) the extent of the main structural features (i.e. faults, shear zones, foliation, and folds) that are present beyond the ore bodies and deposit (J.-L. Pilote, unpub. data, 2014). None of the locally (centimetre-scale) remobilized gold extends outside the deposit, which implies that any structurally controlled gold must have been remobilized from the deposit.

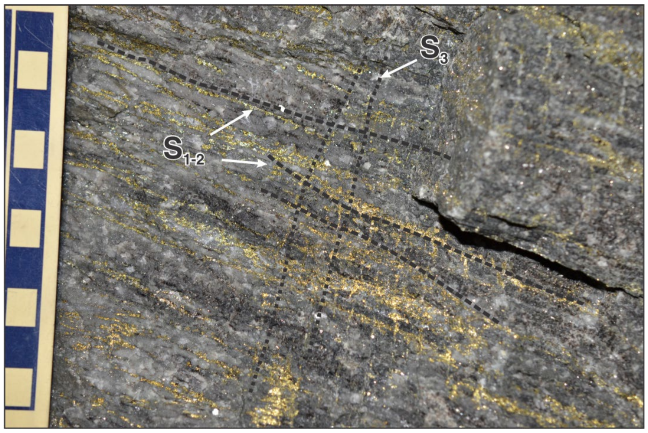

Figure 11. Chalcopyrite veinlets oriented parallel to structural foliations S_{1-2} and overprinted at a high angle by chalcopyrite veinlets oriented in the plane of the S_3 fabric, hosted in an IN2 diorite intruding the massive sulphide in level 434 (1807 zone). View looking northwest, perpendicular to the longitudinal orientation of the massive sulphide; scale is in centimetres. Photograph by J.L. Pilote. 2014-179

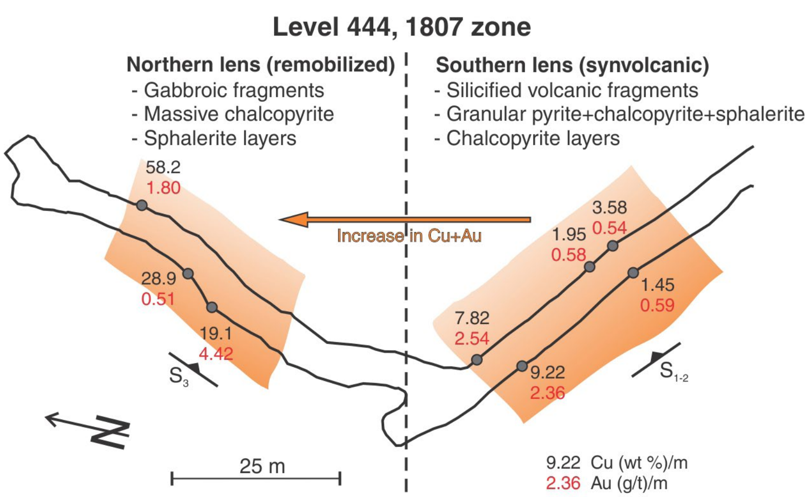

Figure 12. Plan view of level 444 in the 1807 zone. The northern and southern lenses (in orange) show mineralogical, geochemical, structural, and textural distinctions. A general trend is observed with Cu and Au contents increasing toward the north.

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