GEOLOGICAL ENVIRONMENT AND FORMATIONAL CONTROLS OF AURIFEROUS MASSIVE SULFIDE DEPOSITS: AN EXAMPLE FROM THE CAMBRO-ORDOVICIAN CU-AU MING VMS DEPOSIT IN THE NEWFOUNDLAND APPALACHIANS

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INTRODUCTION AND RESEARCH RATIONALE

Some volcanogenic massive sulfide (VMS) deposits are enriched in precious metals, with Au contents (in g/t) that typically exceed the associated Cu+Pb+Zn grades (in wt %) (e.g., Poulsen and Hannington, 1996; Mercier-Langevin et al., 2010). The origin of the Au enrichment in these anomalous VMS deposits is commonly debated (e.g., syngenetic vs. metamorphic overprint). In order to determine the origin of gold enrichment, it is important to constrain the volcano-stratigraphy, deformation, and geodynamic setting in which the VMS deposit was formed. These characteristics are fundamentally important as they represent possible controls to the variation in metal content and the source of precious metals (Mercier-Langevin et al., 2010).

The Ming deposit, located in the northern central Newfoundland Appalachians, is a Au- and Cu-rich VMS that also has locally high Ag and Zn grades. As of 2014, the active Ming mine has reserves (diluted and recovered) of 1.50 Mt grading 1.71 wt% Cu, 0.36 wt% 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 wt% Cu, 0.44 wt% Zn, 9.08 g/t Ag, and 2.15 g/t Au. The deposit comprises four discrete, elongated, north-northeast-plunging (ca. 30-35°) Cu-Au-(Zn-Ag) massive to semi-massive (< 50 vol.%) sulfide lenses that are spaced 30 to 50 metres apart along the same stratigraphic horizon. Herein, we provide preliminary observations on lithologic and alteration features of the host rocks and investigate their genetic relationships with the synvolcanic, precious metal-rich sulfide lenses.

GEOLOGIC SETTING

The Ming Mine is located in the Baie Verte Peninsula (Fig. 1), which straddles the boundary (Baie Verte Brompton Line) between the Humber Zone to the west and a series of ophiolitic complexes and cover volcanic rocks to the east (Fig. 1). The ophiolites comprise mainly suprasubduction-zone rocks of mafic to ultramafic composition, including boninites, collectively termed the Baie Verte Oceanic Tract (BVOT; van Staal, 2007), are disconformably overlain by volcano-sedimentary cover sequences of the Snooks Arm Group (Skulski et al., 2010). Several large Upper Ordovician to Silurian granitoid plutons intrude the BVOT (Figs. 1-2).

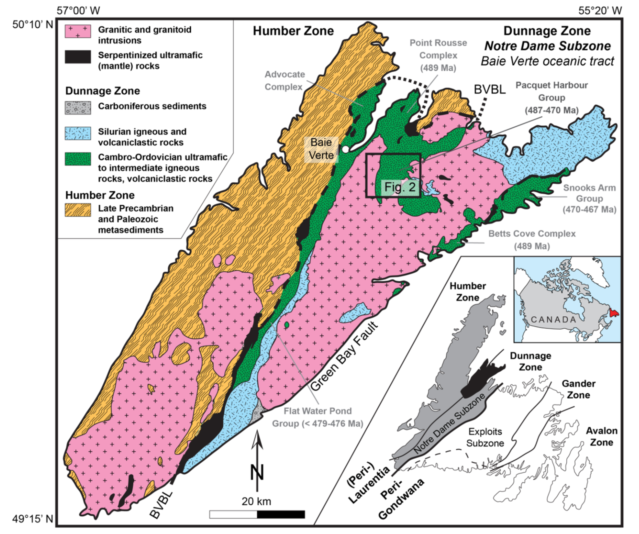
Fig. 1. Simplified geological map of the Baie Verte Peninsula (modified from Skulski et al., 2010, and references therein) with the (peri-)Laurentian (inset: in grey) and (peri-)Gondwanan tectonostratigraphic zones forming the Appalachian orogenic belt in Newfoundland (Williams, 1979). BVBL - Baie Verte-Brompton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

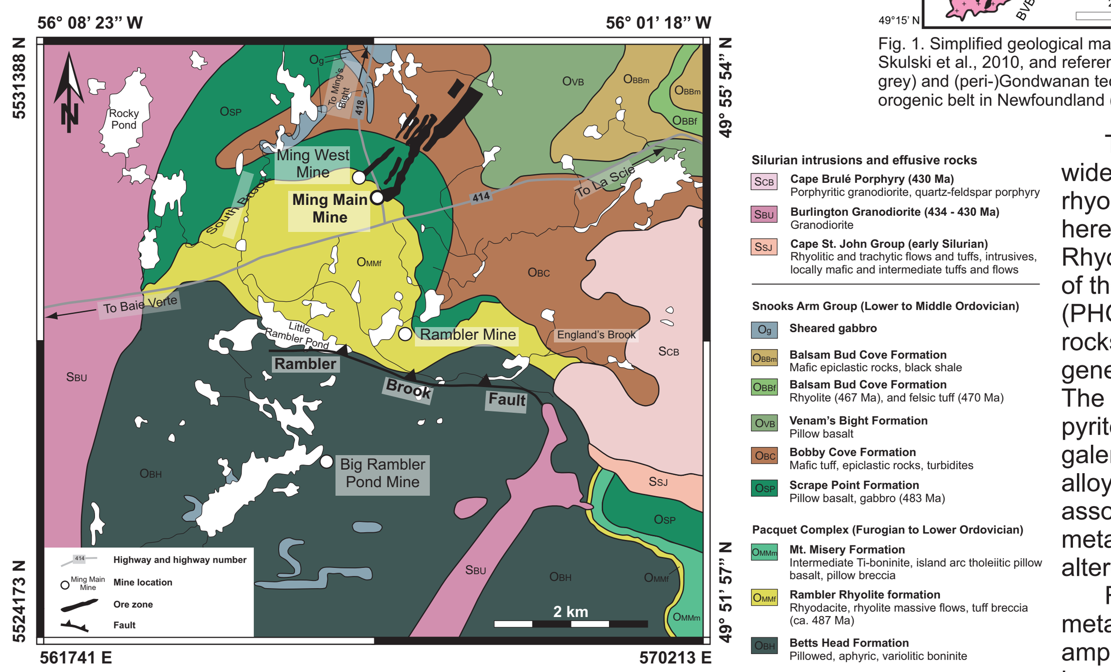

Fig. 2. Regional geology of the study area, Baie Verte Peninsula with Ming VMS orebodies projected to surface and shown in black. Both datums are shown in WGS 84 (top and right) and UTM 21N NAD 83 (bottom and left). Map modified from Pilgrim (2009), Tuach and Kennedy (1978), Castonguay et al. (2009), and Hibbard (1983).

The deposit is hosted by a 2.5 km wide sequence of quartz-pyric rhyodacite, felsic tuff, and tuff breccia, herein referred to as the Rambler Rhyolite formation (Fig. 2), that is part of the lower Pacquet Harbour Group (PHG; or Pacquet Complex). These rocks are intruded by multiple generations of tholeiitic gabbro dykes. The ore consists of chalcopyrite, pyrite, sphalerite, pyrrhotite, minor galena and trace electrum (Au-Ag alloy). The sulfide lenses are spatially associated with several zones of metamorphosed hydrothermally altered footwall rocks.

Rock units of the Ming area were metamorphosed to greenschist to amphibolitic facies and were affected by at least four phases of regional deformation (D_1 to D_4). The main deformation phase, D_2, consists of a penetrative schistosity (S_2) in the Rambler Rhyolite formation and its cover sequences. D_2 is overprinted by discrete cleavage and crenulation associated with D_3 and D_4.

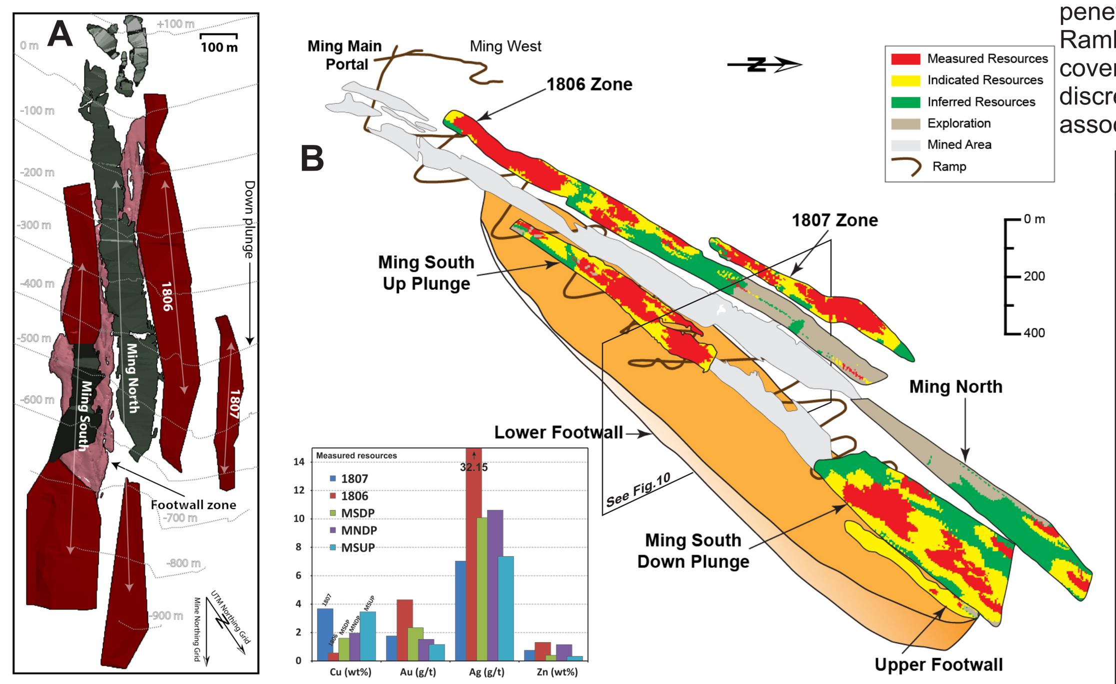

Fig. 3. A) Plan view of the Ming orebodies projected to surface (0m). The surface of wireframes in red represent orebodies currently in production or those that will be mined, whereas those in grey have been previously mined orebodies. B) Oblique view (looking west) of the Ming orebodies with average grade of measured resources.

STRATIGRAPHY

Hanging wall


Fig. 4. Amygdaloidal basalt flow (RM04-04).


Fig. 5. Magnetite-rich siltstone horizon. This unit is considered to form the base of the Snooks Arm cover sequence traced throughout the Baie Verte Peninsula (RM04-04).


Fig. 6. Pods of hydrothermal sulfides (mainly granular pyrite clusters) within a polymictic intermediate lithic lapilli tuff overlying (<5 m from) the massive sulfide lens (RMUG13-205).

Footwall

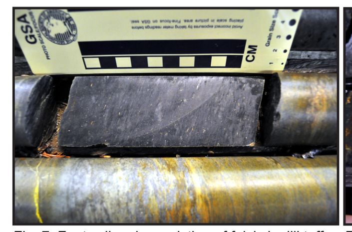
Fig. 7. Footwall rock consisting of felsic lapilli tuff (RM04-04). Note the elongated shape of the lapilli fragments.


Fig. 8. Dark bluish quartz-phyric rhyodacite with abundant chalcopyrite-pyrrhotite-pyrite stringer veinlets (RM04-04).

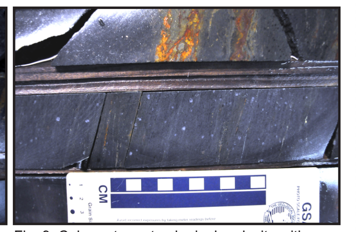
Fig. 9. Coherent quartz-phyric rhyodacite with minor chalcopyrite-phyrrotite stringer veinlets (RM04-04).

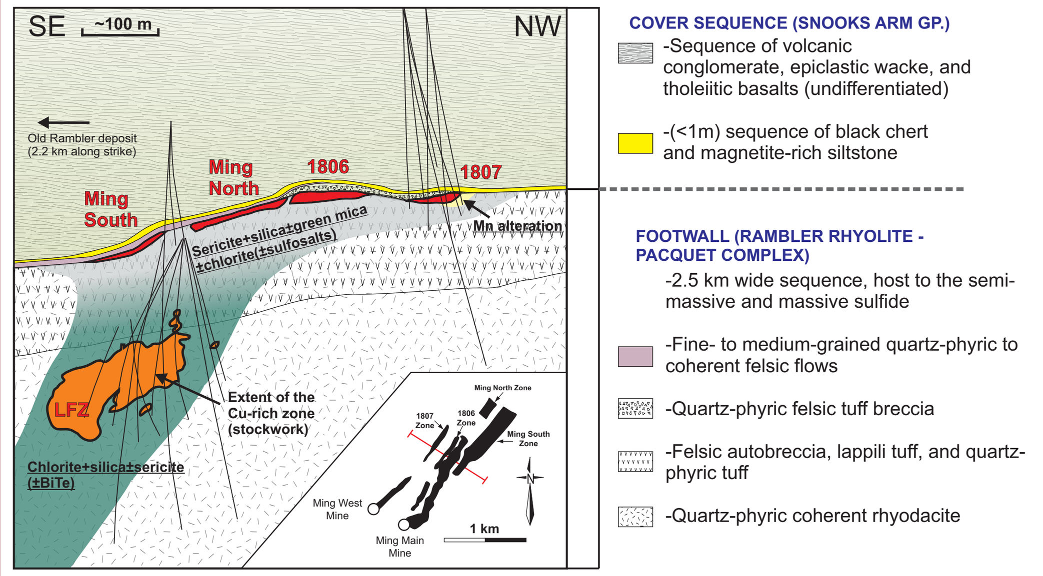

Fig. 10. Schematic cross-section of the Ming deposit showing the main lithologies, massive sulfide orebodies, and alteration assemblages. The inset shows a plan view of the orebodies.

Intrusive rocks

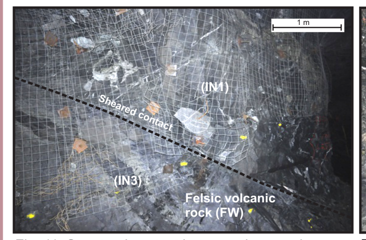

Fig. 11. Structural contact between the massive melanocratic gabbroic dyke (IN1) and the coherent felsic volcanic footwall rocks. The mesocratic hornblende-rich intermediate dyke (IN3) is emplaced near the contact (level 469).

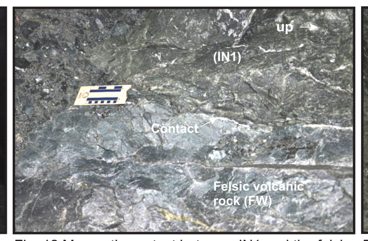

Fig. 12.Magmatic contact between IN1 and the felsic volcanic footwall rocks (level 481).

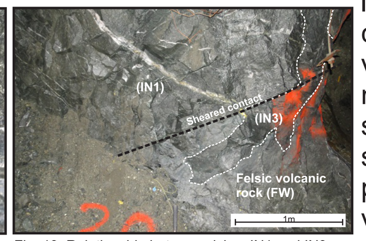

Fig. 13. Relationship between dykes IN1 and IN3 that have been displaced by the structural contact between IN1 and the felsic volcanic footwall rocks shown in Fig. 11 (level 469).

Underground stratigraphic relationships (with Fig. 18)

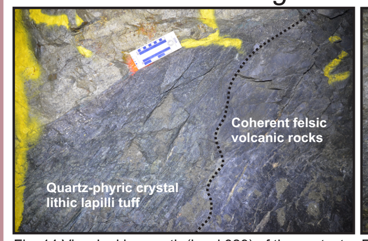

Fig. 14.View looking south (level 329) of the contact between the medium-grained, light green, quartz-phyric crystal lithic lapilli tuff and the deep purple coherent felsic volcanic units underlying the massive sulfide.

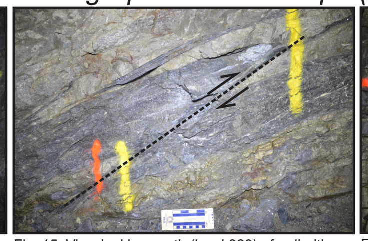
Fig. 15. View looking south (level 329) of a dioritic dyke (IN2) intruding the massive sulfide lens and affected by an apparent reverse fault.

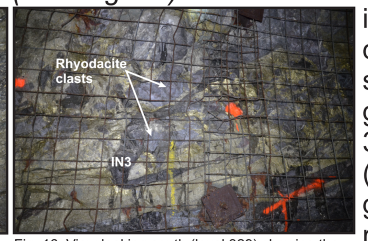

Fig. 16. View looking south (level 329) showing the relationship between the massive sulfide lenses which contains abundant rhyodacite fragments and a boudinaged and folded IN3 dyke.

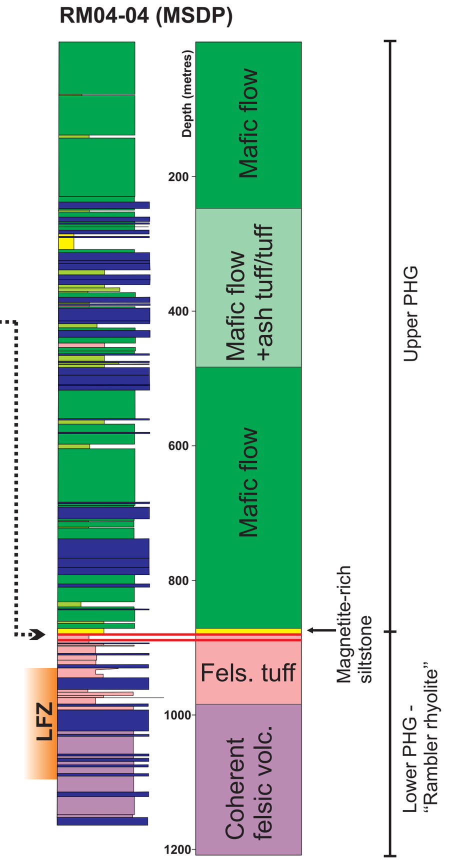

Fig 17. Representative stratigraphic section of the Ming South Down Plunge (MSDP). The red lines represent the two massive sulfide lenses.Blue units represent undifferentiated mafic dykes. The LFZ (Lower Footwall Zone) represents the Cu-rich stockwork underlying part of the Ming deposit.

The footwall rocks consist of two distinct intermediate to felsic units (Figs. 4-18); the lower part predominantly comprises coherent felsic volcanic rocks, whereas volcaniclastic rocks dominate in the upper part (Figs. 7-10, 14, 18). The immediate hanging wall is lithologically heterogeneous, comprising a highly silicified volcaniclastic rock and a magnetite-rich volcanogenic siltstone (Fig. 5). The cover sequence consists of massive to pillowed basaltic flows, volcanogenic sedimentary rocks, mafic tuffs and minor felsic volcanic rocks (Figs 4-6). Three generations of mafic to intermediate sills and dykes intrude the deposit and have distinctive lithogeochemical signatures (Figs. 11-13): 1) grabbro (IN1), 2) diorite (IN2), and 3) a hornblende-rich granodiorite (IN3). These are interpreted to be genetically related to the mafic rocks in the ophiolitic cover sequence that overlies the deposit.

ALTERATION

A ubiquitous low temperature alteration assemblage occur below the 1807, 1806, and Ming South zones (Figs. 10, 19-22). This light to medium grey assemblage consists of sericite-green mica-quartz±chlorite±epidote. The Lower Footwall Zone (LFZ) lies 50m below the latter alteration assemblage and consists of intense chlorite altered rocks, interpreted to mark the high-temperature hydrothermal fluid discharge zone of the deposit. Sulfide mineralogy varies from a polymetallic assemblage in the massive sulfide to a predominantly chalcopyrite-pyrrhotite-pyrite assemblage in the LFZ. A quartz-pyrite-rich core zone occurs immediately above and below the massive sulfide. This quartz-pyrite alteration, which overprints a folded IN3 dyke, is interpreted to be a late-stage feature. A Mn-Ca alteration consisting of a rhodochrosite-(Mn-)garnet-quartz assemblage affects rocks of the 1807 zone. Metamorphic biotite-magnetite-garnet-actinolite porphyroblasts are ubiquitous in the footwall rocks.

1807 | 1806 | Ming South | Lower Footwall

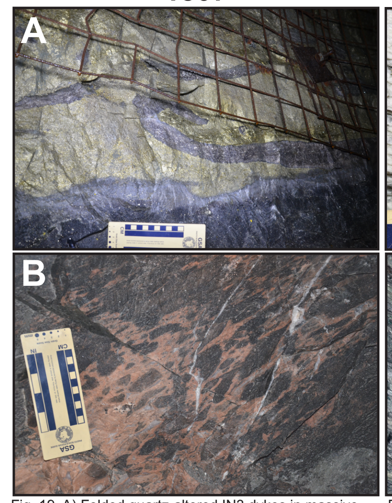
Fig. 19. A) Folded quartz-altered IN3 dykes in massive sulfide and quartz-altered immediate footwall (level 329). B) Mn-alteration in the footwall of level (481).

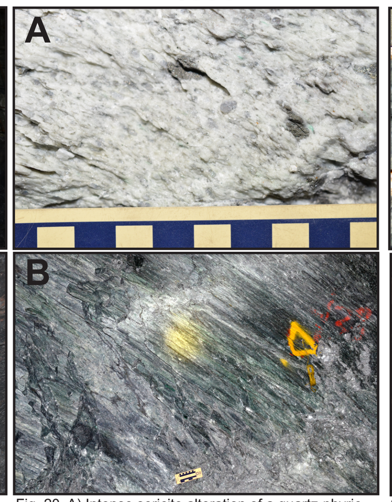
Fig. 20. A) Intense sericite alteration of a quartz-phyric felsic crystal tuff (level 107). B) Intense sericite-green mica (fuchsite) alteration in the footwall rocks (level 107).

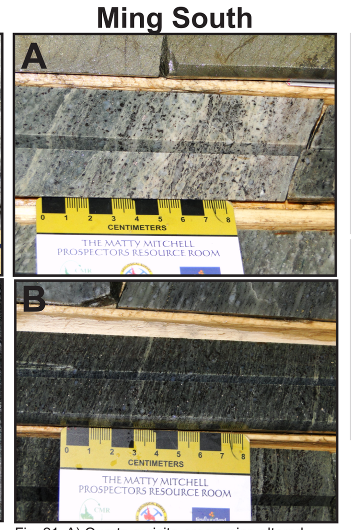
Fig. 21. A) Quartz-sericite-green mica-altered quartz-phyric felsic crystal tuff (RMUG04-06D). B) Sericite-altered quartz-phyric crystal tuff (RMUG04-06D).

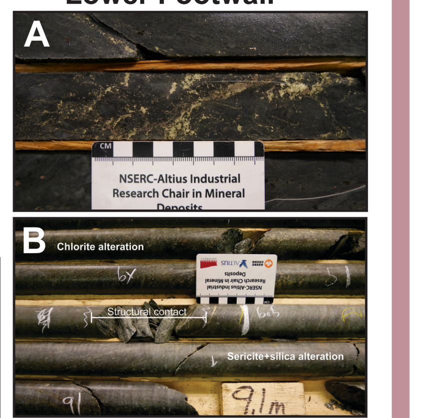
Fig. 22. A) Intense chlorite-altered quartz-phyric coherent felsic volcanic rock with chalcopyrite-pyrrhotite stringer veins transposed parallel to the main fabric (RM04-04). B) Structural contact between a strongly altered felsic volcanic and sericite-quartz altered felsic lapilli tuff (RMUG14-250).

GEOCHEMISTRY

The host volcanic rocks have intermediate to felsic compositions (Fig. 23A) and a calc-alkaline affinity with high Th/Yb and Zr/Y ratios (Fig. 23B), also shown on the extended element plot (Fig.23C). The mafic rocks of the cover sequence and intrusive rocks vary from transitional to calc-alkaline, consistent with the correlative Snooks Arm Group (Skulski et al., 2010). Their low Yb_{CN} values is consistent with a juvenile arc-system (Lesher et al., 1986), however, their $(La/Yb)_{CN}$ values are higher than typical FIII and FIV volcanic rocks (Fig. 23D; Piercey, 2011).

The general element ratio and alteration box plot (Figs. 23E, F) reveal two main alteration trends: 1) an alteration dominated by sericite (higher Al content) near massive sulfide lenses and 2) an Fe-Mg alteration deeper in the footwall rocks.

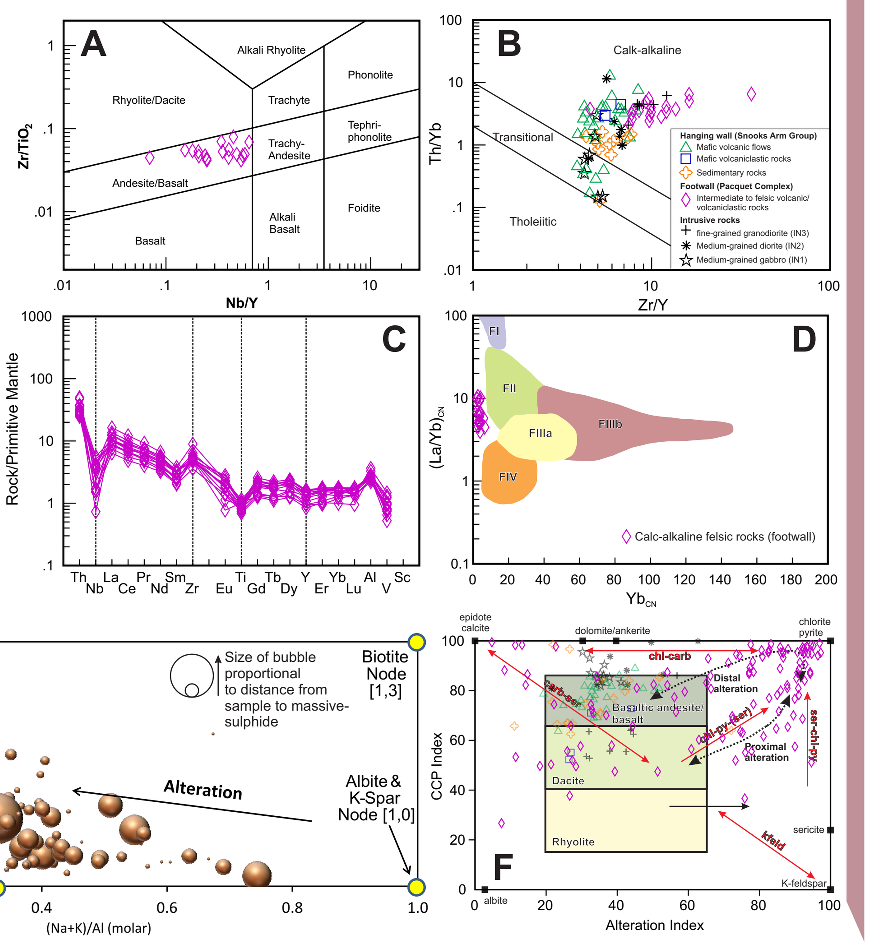

Fig. 23. A) Zr/TiO_2-Nb/Y discrimination diagram of Winchester & Floyd (1977), modified by Pearce (1996). B) Th/Yb-Zr/Y discrimination diagram of Ross and Bédard (2009). C) Primitive mantle-normalized plot with normalized values from Sun and McDonough (1989). D) $(La/Yb)_{CN}$-Yb_{CN} discrimination diagram of Hart et al. (2004). E) General element ratio diagram plotting Na and K against Fe and Mg to test for compositional control by albite and muscovite. Relevant minerals plot at the nodes indicated. F) Box Plot of major element mobility after Large et al. (2001). Arrows show common trends as a result of hydrothermal alteration. Abbreviations: carb, carbonate; chl, chlorite; kfeld, K-feldspar; py, pyrite; ser, sericite; CCP, chlorite-carbonate-pyrite. $CCP=100(MgO+FeO)/(MgO+FeO+Na_2O+K_2O)$ and Alteration Index = $100(K_2O+MgO)/(K2O+MgO+Na_2O+CaO)$. See Fig. 23B for symbol legend.

BASE AND PRECIOUS METAL REMOBILIZATION

The 1806 and 1807 zones exhibit evidence of cm- to orebody-scale mechanical remobilization of the massive sulfides (e.g. massive sulfides piercing in the host rocks) and gold. Gold stringer veins cut foliated (S_2) quartz-sericite altered felsic volcanic rock, less than 1 m from the massive sulfide lens of the 1806 zone (Fig. 24). A mafic dyke (IN2) intruding the massive sulfides on level 434 records multiple generations of chalcopyrite veinlets oriented parallel to the main fabrics (S_{2-4}) (Fig. 25). The massive sulfides in the northern part of the 1807 lens has distinctively higher Cu-Au contents coexisting with thin layers of sphalerite and also contains less silicified volcanic host rock fragments in the massive sulfides than the southern counterpart (Fig. 26). These features provide evidence for local remobilization of metals during deformation and metamorphism.

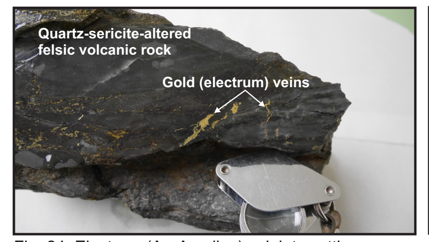

Fig. 24. Electrum (Au-Ag alloy) stringer veins cutting foliated quartz-sericite altered felsic volcanic rock (1806 zone).

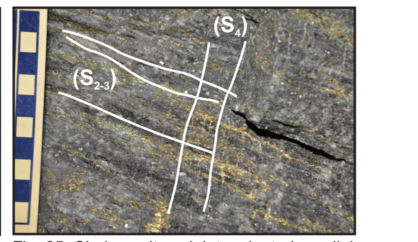
Fig. 25. Chalcopyrite veinlets oriented parallel to the main foliation (S_2) and cut at high-angle by late chalcopyrite veinlets (S_4), in a IN2 diorite intruding the massive sulfide (level 434; 1807 zone).

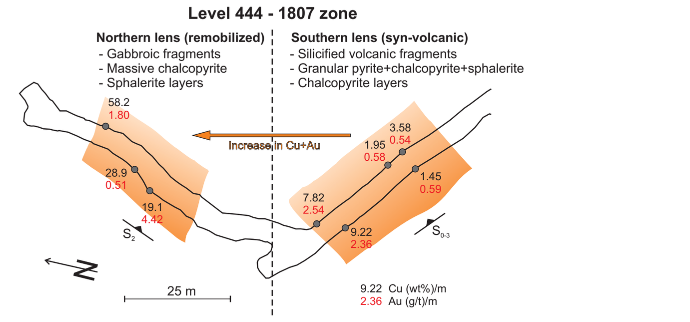

Fig. 26. Map of level 444 in the 1807 zone. The northern and southern lenses (in orange) have mineralogical, geochemical, structural, and textural distinctions. Note the general northward increase of Cu and Au contents.

SYNGENETIC OR OROGENIC PRECIOUS METAL ENRICHMENT?

Despite local mechanical remobilization discussed above of the massive sulfides due to post-mineralization deformation events, evidence for a synvolcanic origin for the massive sulfide lenses and their precious metal enrichment include:

- the spatial distribution of the massive sulfides and their relationship with the host rocks (i.e., stratabound and stratiform in the southern part of the 1807, 1806, and MSDP zones);
- the presence of discordant high temperature (chloritic) and lower temperature proximal (sericitic) hydrothermal alteration assemblages underlying the massive sulphides;
- the presence of Au-barren post-mineralization mafic dykes that cut the orebodies;

Other evidence for a syngenetic model that have not been discuss in length here include:

- the intense deformation of all ore and alteration assemblages;
- the presence of atypical mineralogy with abundant sulfosalts 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
- all structural features (i.e., faults, shear zones, foliation, and folds) that overprint the Ming deposit and extend >100 m beyond the ore bodies are devoid of Au. Remobilized Au is restricted (< 1m) to the immediate footwall and hanging wall of the orebodies. This implies a syngenetic Au introduction in the massive sulfide and that Au was later remobilized during deformation events.

PRELIMINARY CONCLUSIONS

- The Ming VMS deposit is enriched in Cu and Au (also Zn and Ag);
- Ming is characterized by three alteration assemblages (i.e. chlorite, sericite, and Mn);
- Petrochemistry reveals a juvenile affinity for the felsic volcanic rocks;
- The VMS deposit was formed during the evolution of a supra-subduction zone;
- Massive sulfide lenses were structurally remobilized as stringer veinlets and piercement structures into the host rock and intrusions;
- Gold was locally remobilized, together with other metals due to deformation;
- This study supports a syngenetic precious-metal enrichment of a VMS.

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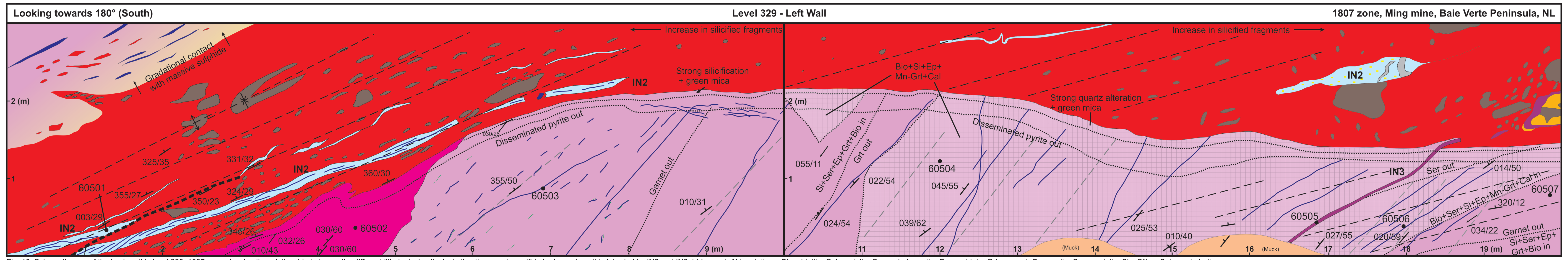

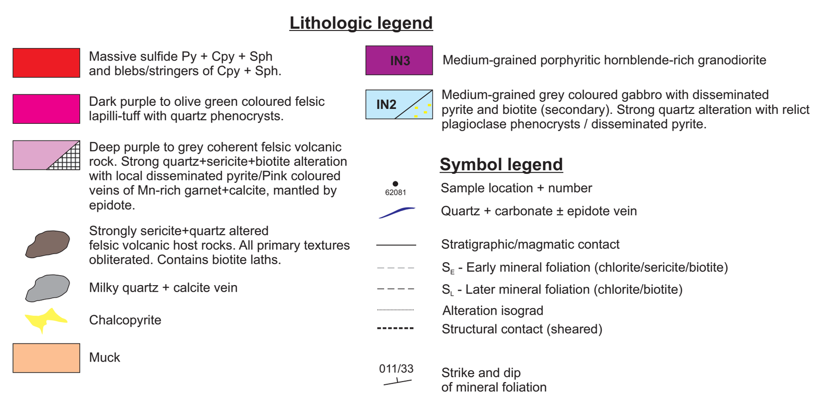

Fig. 18. Schematic map of the back wall in level 329, 1807 zone showing the relationship between the different lithological units, including the massive sulfide horizon where it is intruded by IN2 and IN3; b) Legend. Abbreviations: Bio – biotite, Cal – calcite, Cpy – chalcopyrite, Ep – epidote, Grt – garnet, Py – pyrite, Ser – sericite, Si – Silica, Sph – sphalerite.

REFERENCES

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