Geology and gold enrichment at the Horne 5 Archean volcanogenic massive sulphide deposit, Abitibi greenstone belt, Quebec: A synthesis

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ABSTRACT

The Archean Horne 5 volcanogenic massive sulphide deposit contains total resources of 172.6 t Au (5.6 Moz; 112.7 Mt at 1.53 g/t Au) with significant Ag, Cu, and Zn as by-products, one of the world's largest volcanogenic massive sulphide-associated gold resource. The deposit consists of stacked massive to semi-massive sulphide lenses that alternate with extensive zones of disseminated and stringer sulphides enclosed within steeply dipping felsic volcaniclastic and shallow synvolcanic intrusive units of transitional to calc-alkaline magmatic affinity. Massive sulphide clasts are locally abundant in the volcaniclastic rocks at several stratigraphic positions.

Gold is interpreted to be synvolcanic and is spatially associated with an assemblage primarily composed of pyrite, sphalerite, and chalcopyrite. Gold distribution in the Horne 5 deposit is largely controlled by the higher porosity and permeability of select host lithologies (fragmental felsic units), which facilitate hydrothermal fluid circulation in the subseafloor environment. The presence of felsic synvolcanic intrusions and fine-grained tuffs overlying auriferous zones also influences the distribution of the mineralization by acting as impermeable cap rocks to ascending fluids. Although part of the mineralization formed below the seafloor, the presence of massive sulphide clasts indicates that sulphide mounds also accumulated on or close to the seafloor. The architecture of the Horne 5 deposit is characterized by along-strike zonation of two dominant metal assemblages, i.e., Zn±Au and Cu-Au, with the Cu-Au assemblage likely representing higher temperature discharge sites. However, the original geometry of the deposit was modified when it was tilted and transposed along the east-west foliation during deformation and metamorphism. Remobilization of metals due to metamorphism and deformation likely occurred at the micro-scale and resulted primarily in the exsolution of gold and its associated trace elements from recrystallized pyrite.

This study provides further evidence for a major synvolcanic gold event in the southern Abitibi. It indicates that the Horne deposit is associated with calc-alkaline felsic volcanic rocks and is consistent with the preferential association between Archean synvolcanic gold and the early phases of rifting of a thickened arc crust towards the end of the southern Abitibi greenstone belt volcano-magmatic construction.

INTRODUCTION

The Horne 5 volcanogenic massive sulphide (VMS) deposit is currently one of the largest gold exploration targets in Canada. Resources are estimated at 112.7 Mt at 1.53 g/t Au (172.6 t or 5.6 Moz Au: www.falcores.com), with significant Ag, Cu, and Zn as by-products. The Horne 5 deposit is located in the Noranda camp in the southern part of the Archean Abitibi greenstone belt (Fig. 1), downdip of the historic Horne mine workings (Fig. 2). The Horne mine is the largest known example of gold-rich VMS mineralization, with a production history of 53.7 Mt of ore at 6.06 g/t Au (325.4 t or 10.5 Moz Au), 2.2% Cu, and 13.0 g/t Ag (Mercier-Langevin et al., 2011a), extracted largely from the Upper H and Lower H orebodies between 1927 and 1976 (Kerr and Mason, 1990; Cattalani et al., 1993).

Access to new material from the Horne 5 deposit following exploration drilling by Falco Resources provides an ideal opportunity to study gold-enrichment processes in a large Archean synvolcanic system (Krushnisky, 2018; Krushnisky et al., in prep). The results of this study are based on detailed drill core log-

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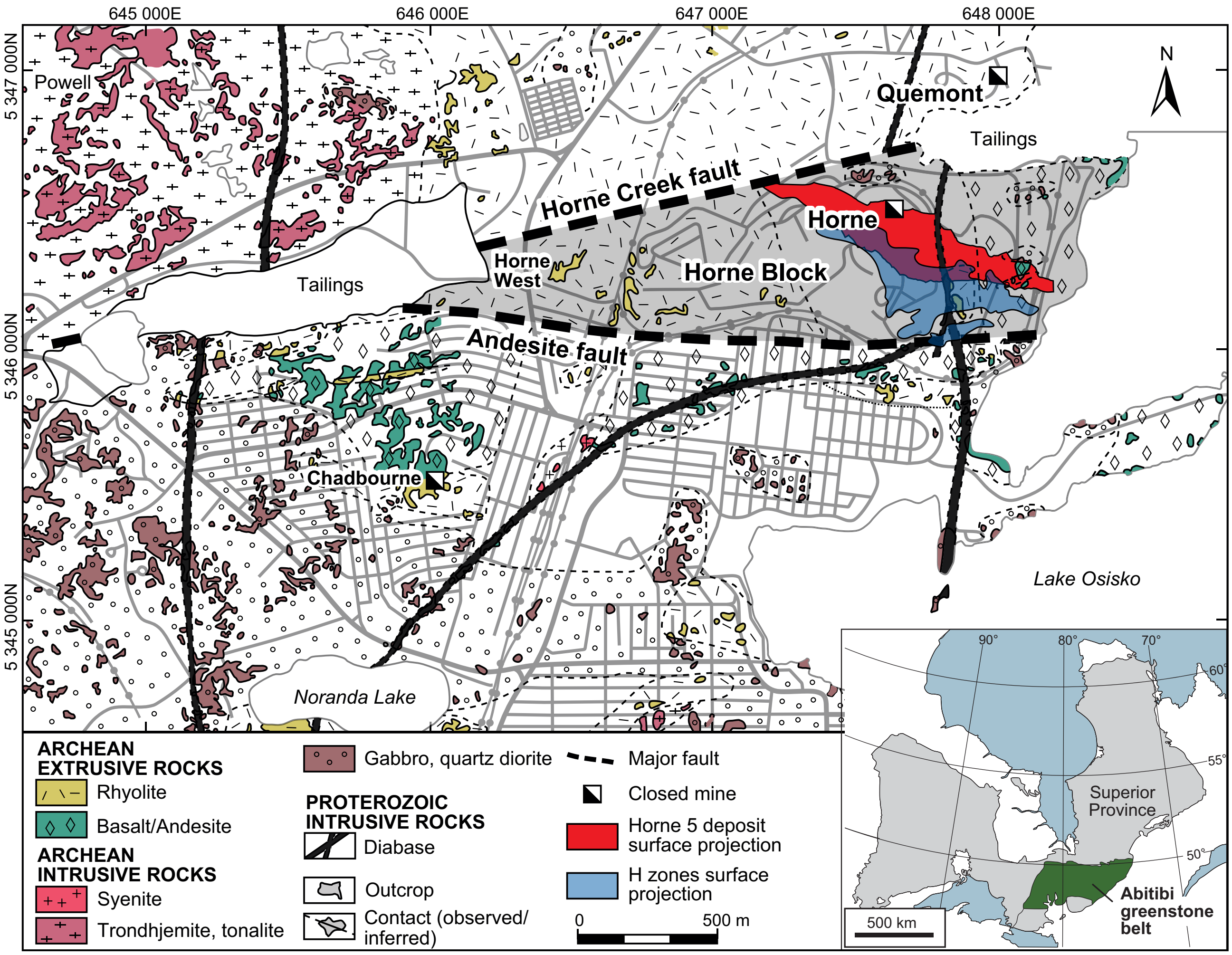


Figure 1. Geological map of the Horne Block (*modified from* Monecke et al., 2008). The trace of the Horne 5 lens (in red) and the Upper and Lower H zones (in blue; from Cattalani et al., 1993) are projected to the surface. Map coordinates are in UTM NAD83 Zone 17.

ging and sampling, whole-rock lithogeochemistry (Krushnisky et al., 2018), petrography, 3-D modeling, and micro-analyses of sulphide and alteration minerals. This project aims to provide a detailed documentation of the volcanic, hydrothermal, and structural context of the Horne 5 deposit to determine the principal controls on the timing and distribution of gold mineralization at various scales and to assess the effects of the deformation and metamorphism on gold remobilization.

This contribution presents a summary of the project that was conducted in collaboration between Natural Resources Canada, the Institut national de la Recherche scientifique, Falco Resources Limited, and the Ministère de l'Énergie et des Ressources naturelles du Québec. Readers are referred to Krushnisky (2018) and Krushnisky et al. (2018, in prep) for details.

GEOLOGICAL SETTING

The Horne 5 deposit is located in the Blake River Group within the southern Abitibi greenstone belt (Fig. 1). The 2704–2695 Ma Blake River Group consists of a sequence of subalkaline mafic to felsic volcanic rocks intruded by syn- to post-volcanic plutons and dykes (Dimroth et al., 1982; Piercey et al., 2008; Mueller et al., 2012; McNicoll et al., 2014). The geodynamic setting of the Blake River Group is interpreted to be analogous to modern island arc environments (e.g. the eastern Manus Basin of Papua New Guinea; Dimroth et al., 1983a,b; Mercier-Langevin et al., 2007; Monecke et al., 2017). The Blake River Group hosts a large number of VMS and Au-VMS deposits, which are mostly associated with rifting of the arc crust centred on the Noranda camp (Gibson, 1989; Gibson and Galley, 2007). An alternative to the rift model suggests that the Blake River Group is an ancient mega-caldera complex that hosts VMS mineralization along caldera structures (Mueller et al., 2009; Pearson and Daigneault, 2009; Moore et al., 2016).

Horne Block

The Horne 5 deposit lies in a structural wedge of felsic volcanic rocks referred to as the Horne Block, which is

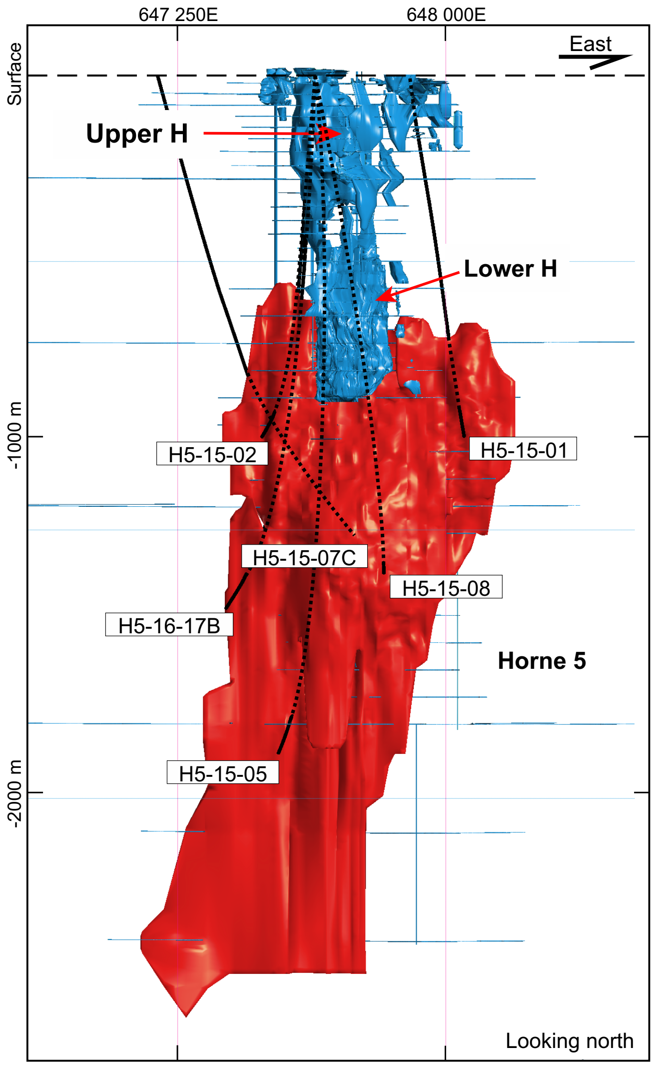


Figure 2. Three-dimensional model of the Horne 5 deposit (in red) showing the six drillholes that were relogged in detail and sampled during this project. The Horne mine workings are also shown in blue.

bound by the Horne Creek fault (north) and Andesite fault (south; Fig. 1). The volcanic rocks consist of dacitic to rhyolitic flows and domes with large volumes of associated volcaniclastic rocks, as well as minor pyroclastic rocks (Price, 1934; Sinclair, 1971; Kerr and Mason, 1990; Kerr and Gibson, 1993; Gibson et al., 2000). High-precision U-Pb dating of a coherent rhyolite in the lowermost part of the Horne sequence (2702.2 ± 0.9 Ma: McNicoll et al., 2014) indicates that the rocks in the block are amongst the oldest in the Blake River Group and predate the volcanic sequence of the Noranda Main camp and its archetypal Cu-Zn VMS deposits by approximately three to four million years.

Deformation within the Horne Block is considered moderate in intensity and is characterized by an east-west-oriented, subvertical foliation (Price, 1948; Barrett et al., 1991; Cattalani et al., 1993). The stretching lineation is vertical near the Andesite fault and inclined at 80°E near the Horne Creek fault (Cattalani et al., 1993). Regional metamorphism reached greenschist facies in the area (Dimroth et al., 1983b; Powell et al., 1995).

GEOLOGY OF THE HORNE 5 DEPOSIT

Volcanology and Lithogeochemistry of the Host Units

The Horne 5 deposit is hosted in a succession of felsic volcaniclastic rocks of transitional to calc-alkaline magmatic affinity (Krushnisky, 2018). This felsic package is steeply inclined, dips and faces north to north-northeast and is oriented west-northwest to east-southeast (Fig. 3; Price, 1934; Sinclair, 1971). Diagenesis, hydrothermal alteration, metamorphism, and deformation have affected these rocks to varying degrees, but in general, primary volcanic textures are relatively well preserved. The felsic succession is stratigraphically overlain by a number of calc-alkaline to tholeiitic basaltic intrusions that occupy the northern portion of the Horne Block up to the Horne Creek fault (Fig. 3).

Horne 5 footwall rhyolite

A series of coherent, felsic rocks and related in-situ breccia or pseudo-breccia are present locally in the footwall of the mineralized zones. These rocks are characterized by rhyolitic compositions (Fig. 4a,b: footwall rhyolite), with SiO_2 values generally above 73 wt% and by a transitional to calc-alkaline magmatic affinity (Fig. 4c).

Dacitic-rhyodacitic volcaniclastic and shallow intrusive unit

Volcaniclastic rocks of dacitic to rhyodacitic compositions (Fig. 4a,b: dacitic-rhyodacitic volcaniclastic rocks) are the principal hosts to the Horne 5 mineralized zones. Although felsic rocks in the Horne Block were mostly considered to be tholeiitic in past studies (Kerr and Mason, 1990; Barrett et al., 1991; Cattalani et al., 1993; Kerr and Gibson, 1993), this study demonstrates that the rocks hosting the Horne 5 deposit are in fact of calc-alkaline to transitional magmatic affinity (Fig. 4c; Krushnisky et al., 2018). This unit extends into the footwall and hanging wall of the deposit.

The volcaniclastic rocks are composed dominantly of aphanitic dacitic-rhyodacitic clasts, some of which exhibit flow-banding textures. Strongly vesicular sericite-rich clasts and massive sulphide fragments are also present throughout. Two principal fragmental facies are recognized: 1) moderately to poorly sorted lapilli tuff to tuff breccia, and 2) graded tuff occurs predominantly towards the stratigraphic upper portion of

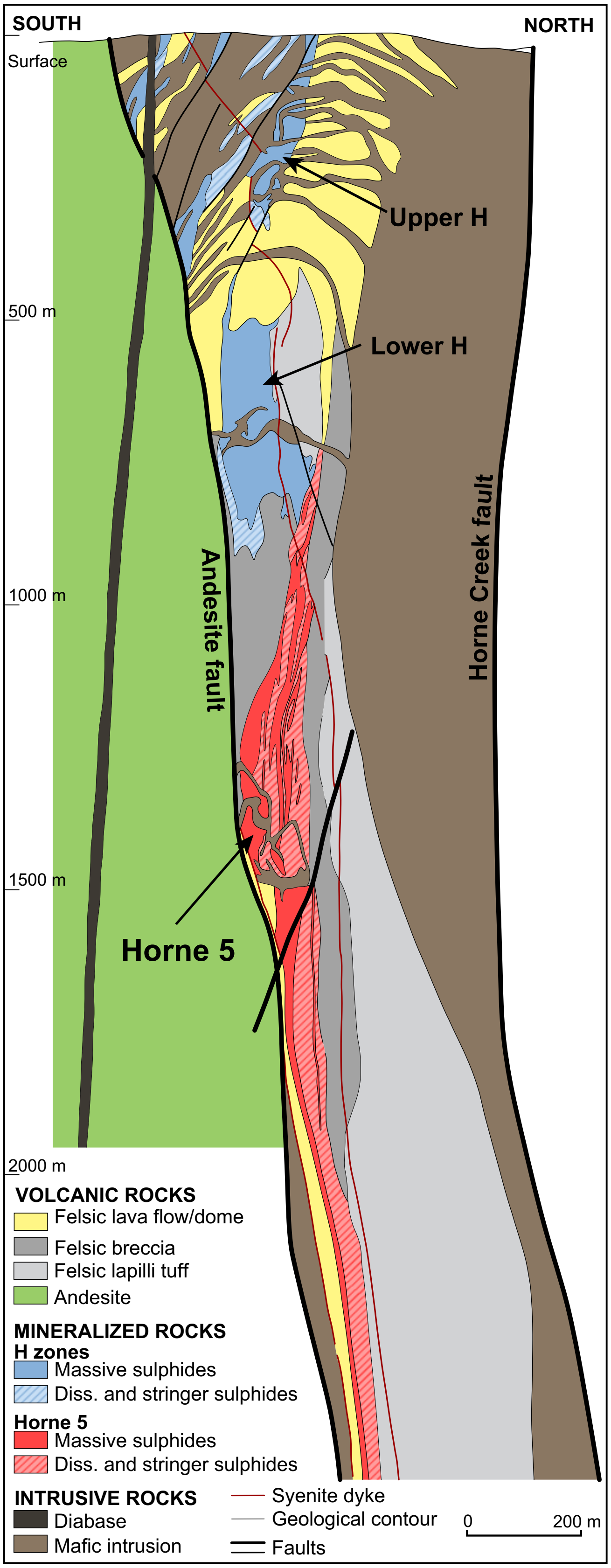


Figure 3. North-south composite section of the Horne Block at 647760 m E, showing the principal lenses of the Horne deposit (*modified from* Cattalani et al., 1993).

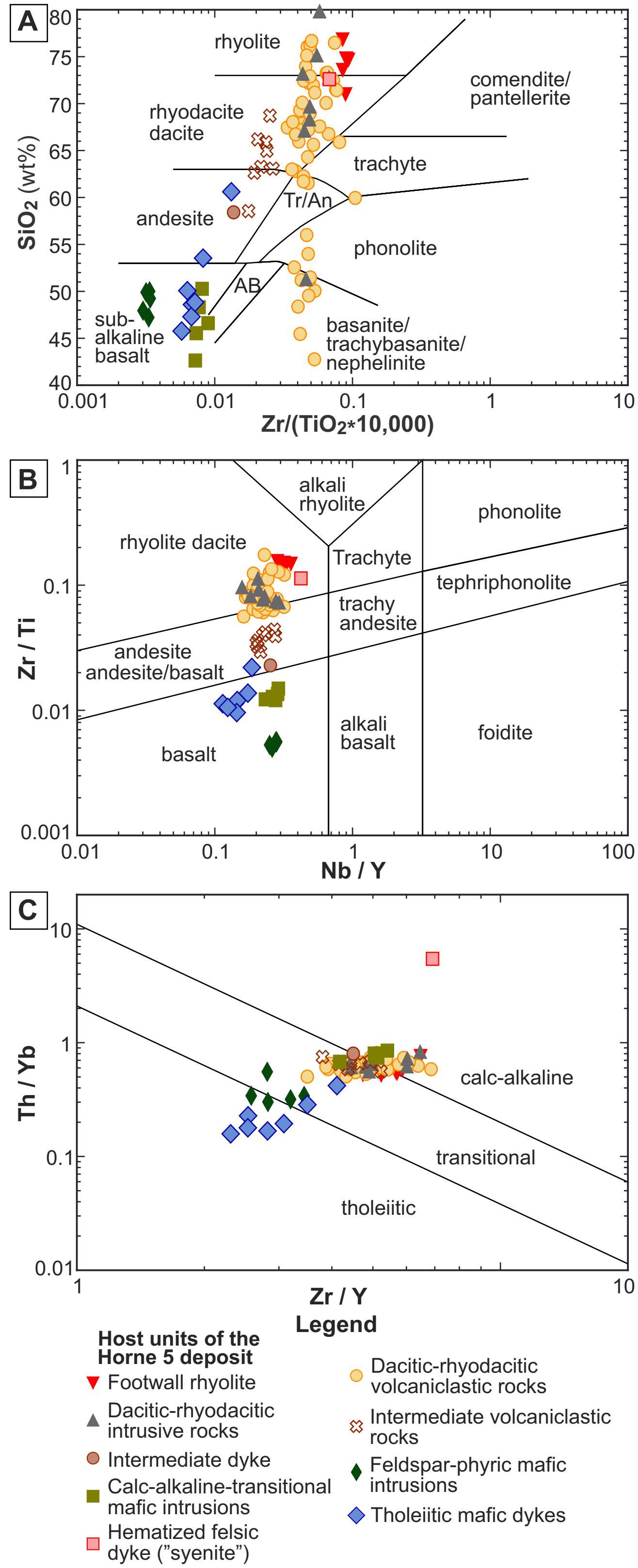


Figure 4. Major and trace element plots of the host units of the Horne 5 deposit. **a)** SiO_2 versus $Zr/(TiO_2*10,000)$ classification diagram of Winchester and Floyd (1977). **b)** Zr/Ti versus Nb/Y classification diagram of Pearce (1996). **c)** Th/Yb versus Zr/Y diagram for discrimination of magmatic affinities from Ross and Bédard (2009).

the mineralized zones and in the hanging wall. The volcaniclastic rocks are inferred to have formed from mass flows associated with fragmentation and mass wasting of felsic lava flows or domes upslope on a submarine volcanic edifice (Krushnisky, 2018).

A series of felsic coherent rocks intruding into the fragmental rocks are also part of this unit. The presence of peperite along the margins of some of the intrusions indicates that they were emplaced in water-saturated, non-consolidated fragmental rocks. They are interpreted as felsic synvolcanic sills that intruded the volcaniclastic rocks at relatively shallow depths below the seafloor. These intrusions closely resemble the felsic clasts of the volcaniclastic rocks in mineralogy, textures, and geochemistry (Fig. 4a–c: dacitic-rhyodacitic intrusive rocks), suggesting a petrogenetic link (Krushnisky, 2018; Krushnisky et al., in prep).

Intermediate volcaniclastic unit

Volcaniclastic rocks characterized by intermediate compositions (Fig. 4a,b: intermediate volcaniclastic rocks) and transitional magmatic affinities (Fig. 4c) are present along two horizons in the hanging wall of the mineralized zones, intercalated with the dacitic-rhyodacitic volcaniclastic rocks. In addition to felsic clasts, the intermediate volcaniclastic rocks contain a high proportion of intermediate to mafic clasts within a matrix composed of chlorite, sericite, and epidote-altered relict amphibole crystals, giving them a distinctly polymictic appearance.

Hanging-wall mafic intrusions

An intermediate dyke of transitional magmatic affinity (Fig. 4a–c: intermediate dyke) intrudes the felsic volcaniclastic rocks in the hanging wall of the mineralized zones. This feldspar and quartz-phyric intrusion contains abundant quartz-pyrite-epidote amygdules.

A unit of feldspar-phyric mafic intrusions overlies the dacitic-rhyodacitic volcaniclastic rocks and is characterized by a basaltic composition (Fig. 4a,b: feldspar-phyric mafic intrusions) and a transitional to tholeiitic magmatic affinity (Fig. 4c). This unit has a distinctive porphyritic texture with 5–20 vol.% feldspar and 5–15 vol.% amphibole and pyroxene phenocrysts.

Mafic intrusions of calc-alkaline to transitional magmatic affinities (Fig. 4c: calc-alkaline-transitional mafic intrusions) and subalkaline to alkaline basaltic compositions (Fig. 4a,b) occur between the feldspar-phyric intrusion and the Horne Creek fault. These intrusions are coarser grained and contain 10–40 vol.% amphibole and 5–20 vol.% feldspar in a heavily chloritized groundmass.

A series of dark green mafic dykes crosscut the Horne 5 stratigraphic succession. The dykes are characterized by a basaltic composition (Fig. 4a,b: tholeiitic mafic dykes) and a tholeiitic to transitional magmatic affinity (Fig. 4c). Their groundmass is very fine-grained (<0.1–0.2 mm) and strongly altered to chlorite and epidote, with minor sericite, magnetite, and pyrite.

Hematized felsic dykes ("syenites")

The volcanic and intrusive succession of the Horne Block is crosscut by a series of dark red to grey-red felsic dykes (Price, 1934; Barrett et al., 1991). Some of these dykes crosscut massive sulphide lenses in the Horne 5 mineralized zones. Although these felsic dykes are often referred to as syenites in the literature, Price (1934) noted important compositional variations that ranged from granitic to syenitic compositions throughout the Horne Block. Petrographic observations from this study agree with the more granitic to tonalitic compositions, with high quartz content (30 vol.%: Krushnisky, 2018). Whole-rock geochemistry for the relatively few samples available indicates a rhyolitic to dacitic composition (Fig. 4a,b) and a calc-alkaline magmatic affinity (Fig. 4c).

Hydrothermal Alteration

The Horne 5 mineralized zones are associated with a broad halo of sericite, which extends 100s of metres along strike and >1500 m along dip from the deposit and contains several higher intensity alteration zones. Although greenschist-facies metamorphism may have recrystallized some of the primary alteration phases to secondary minerals, metamorphic changes to the overall rock chemistry are considered minimal and local in scale, since no significant metasomatic textures are present (e.g. no large-scale veins indicating the passage of large quantities of metamorphic fluids, no coarse-grained altered volcanic rocks indicating high metamorphic grades; Krushnisky, 2018).

Moderate sericite-chlorite-epidote alteration

The sericite-chlorite-epidote alteration assemblage affects most of the dacitic-rhyodacitic unit, from the hanging wall to the footwall of the Horne 5 deposit. Partially preserved volcanic textures and Hashimoto alteration index (AI: Ishikawa et al., 1976; Fig. 5) values range from 20 to 55, indicating a moderate alteration intensity (Gifkins et al., 2005). Alteration phases are restricted to the matrix of volcaniclastic rocks, clast margins, fractures, and phenocrysts, and include foliated sericite (10–25 vol.%) and chlorite (5–15 vol.%), disseminated epidote (1–10 vol.%), and <5 vol.% pyrite, albite, carbonate, and hematite (Fig. 6a). This assemblage is associated with weak losses in Na_2O, very weak gains in MgO and CaO, and gains in FeO^T and SiO_2 (Krushnisky, 2018).

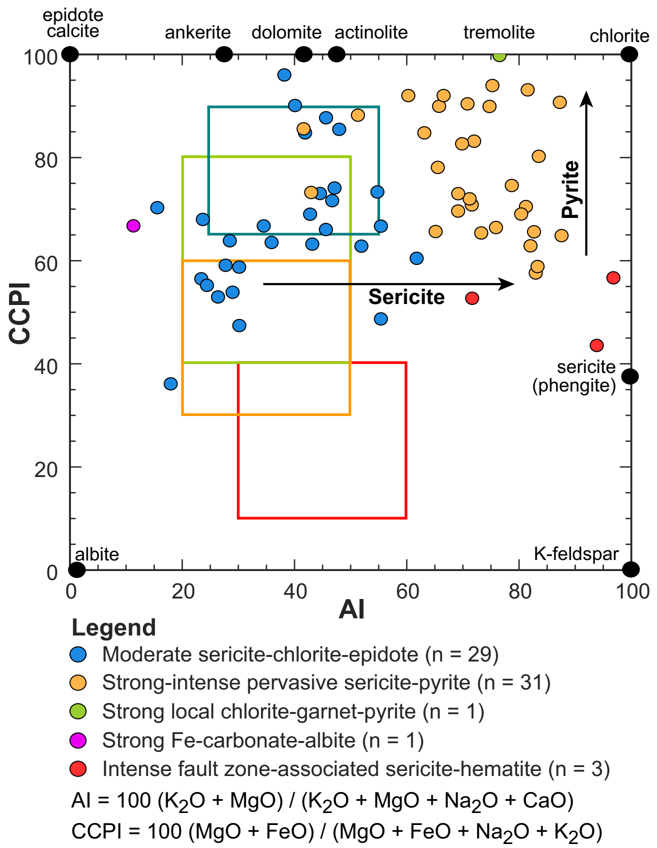


Figure 5. Alteration box plot of Large et al. (2001) for the principal alteration facies within the Horne 5 dacitic-rhyodacitic unit. Coloured rectangles in the alteration box plot represent least altered fields (*from* Gifkins et al., 2005): red = rhyolite least altered field, orange = dacite field, green = andesite field, blue = basalt field.

Strong to intense pervasive sericite-pyrite

Rocks within 10s of metres of massive sulphide lenses are characterized by strong gains in FeO^T and K_2O and leaching of MgO, CaO, and Na_2O. The abundance of strongly foliated sericite and disseminated to massive pyrite imparts a bleached appearance to the host rocks (Fig. 6b). Spessartine garnets occur locally in the footwall and contain 26.9 to 29.3 wt% MnO (Krushnisky, 2018).

The zonation from distal, moderately altered rocks to proximal, intensely altered zones at Horne 5 forms a trend of increasing AI and chlorite-carbonate-pyrite index (CCPI: Large et al., 2001) values that reflect the increasing relative abundance of sericite and pyrite towards the mineralized zones (Fig. 5). Variations in mineral chemistry are also present, with changes in white mica and epidote composition and increases in Mn content in chlorite and carbonate towards the mineralized zones (Krushnisky, 2018).

Strong local chlorite-garnet-pyrite

A few bands of strongly chloritized rocks (≤2 m in thickness) crosscut the moderate sericite-chlorite-epidote assemblage locally in the hanging wall of the mineralized zones. Foliated bands of chlorite (25–30 vol.%) associated with approximately 5 vol.% garnet and pyrite, and <5 vol.% carbonate and magnetite, overprint the felsic volcaniclastic rocks (Fig. 6c). Geochemically, this assemblage plots near the chlorite pole in the alteration box plot (Fig. 5) and is characterized by strong gains in FeO^T and MgO, and losses in CaO, Na_2O, and K_2O.

Strong local Fe-carbonate-albite

Local magnetite-chalcopyrite mineralization is associated with an alteration assemblage comprising siderite, ankerite, and albite, with minor quartz and chlorite. Carbonate generally occur interstitially within massive magnetite along with chalcopyrite and pyrite, and locally appear to be intergrown with magnetite grains. This assemblage is characterized by low AI values (Fig. 5) and important gains in FeO^T and Na_2O.

Intense fault zone-associated sericite-hematite

A fault zone crosscuts the felsic volcaniclastic rocks in the hanging wall of the mineralized zone in drill hole H5-15-05. Faulted rocks are intensely altered and lack any recognizable primary volcanic features. The associated alteration assemblage is characterized by pervasive sericite, fracture-controlled chlorite and carbonate, and disseminated hematite. This assemblage plots towards the sericite pole on the alteration box plot (Fig. 5) and shows strong overall mass losses with leaching of most elements, except for a strong gain in K_2O and a weaker gain in MgO.

Chlorite-epidote-sericite alteration of mafic intrusions

Most intermediate to mafic intrusions at Horne 5 are weakly altered, showing mostly an increase in CCPI. Alteration phases include weakly foliated chlorite and sericite, disseminated epidote and quartz-carbonate veinlets (Fig. 6d). Tholeiitic mafic dykes are the most strongly altered of the intrusions, with the intensity of alteration increasing for samples closer to or within the Horne 5 mineralized zones.

GOLD AND SULPHIDE MINERALIZATION

Geometry of the Mineralized Zones

The Horne 5 deposit consists of a low-grade mineralized envelope (Fig. 2), defined at a cut-off grade of 0.5 g/t Au, that encloses a number of high-grade Au (≥2.5 g/t), Cu (≥0.2 wt%), and Zn (≥0.75 wt%) zones. The mineralized envelope presently lies in a subvertical position that extends from 600 m below the surface to a depth of at least 2500 m and is oriented subparallel to the local felsic stratigraphy.

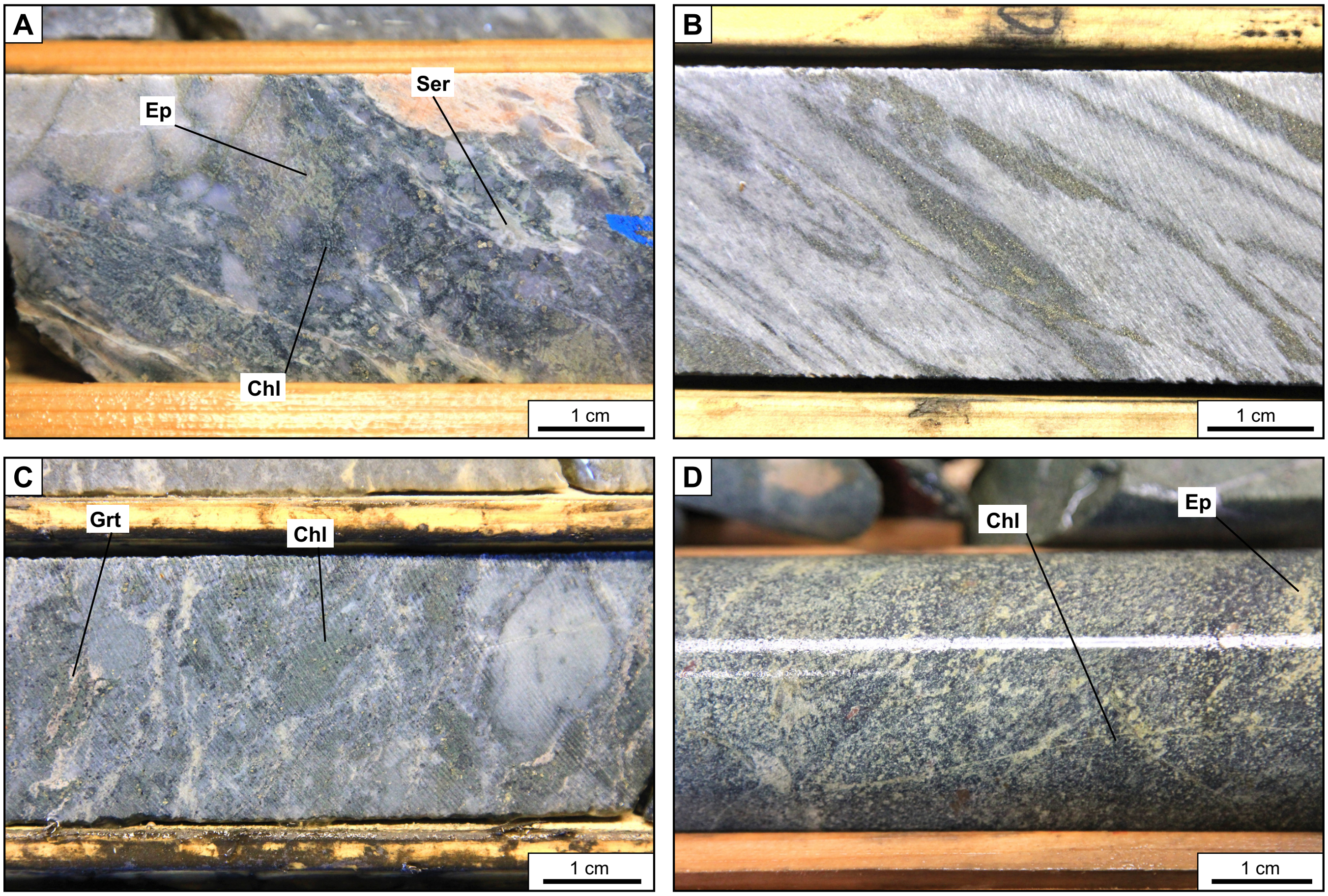


Figure 6. a) Moderate sericite-chlorite-epidote alteration assemblage in felsic volcaniclastic rocks (ddh H5-15-02, 975 m). **b)** Intense pervasive sericite-pyrite alteration assemblage typical of the mineralized intervals (ddh H5-15-02, 1067 m). **c)** Chlorite-garnet-pyrite alteration in a felsic volcaniclastic rock (ddh H5-15-02, 1140 m). **d)** Chlorite-sericite-epidote alteration assemblage in a mafic intrusive rock (ddh H5-15-02, 895 m). Abbreviations: Chl = chlorite, ddh = diamond drillhole, Ep = epidote, Grt = garnet, Ser = sericite.

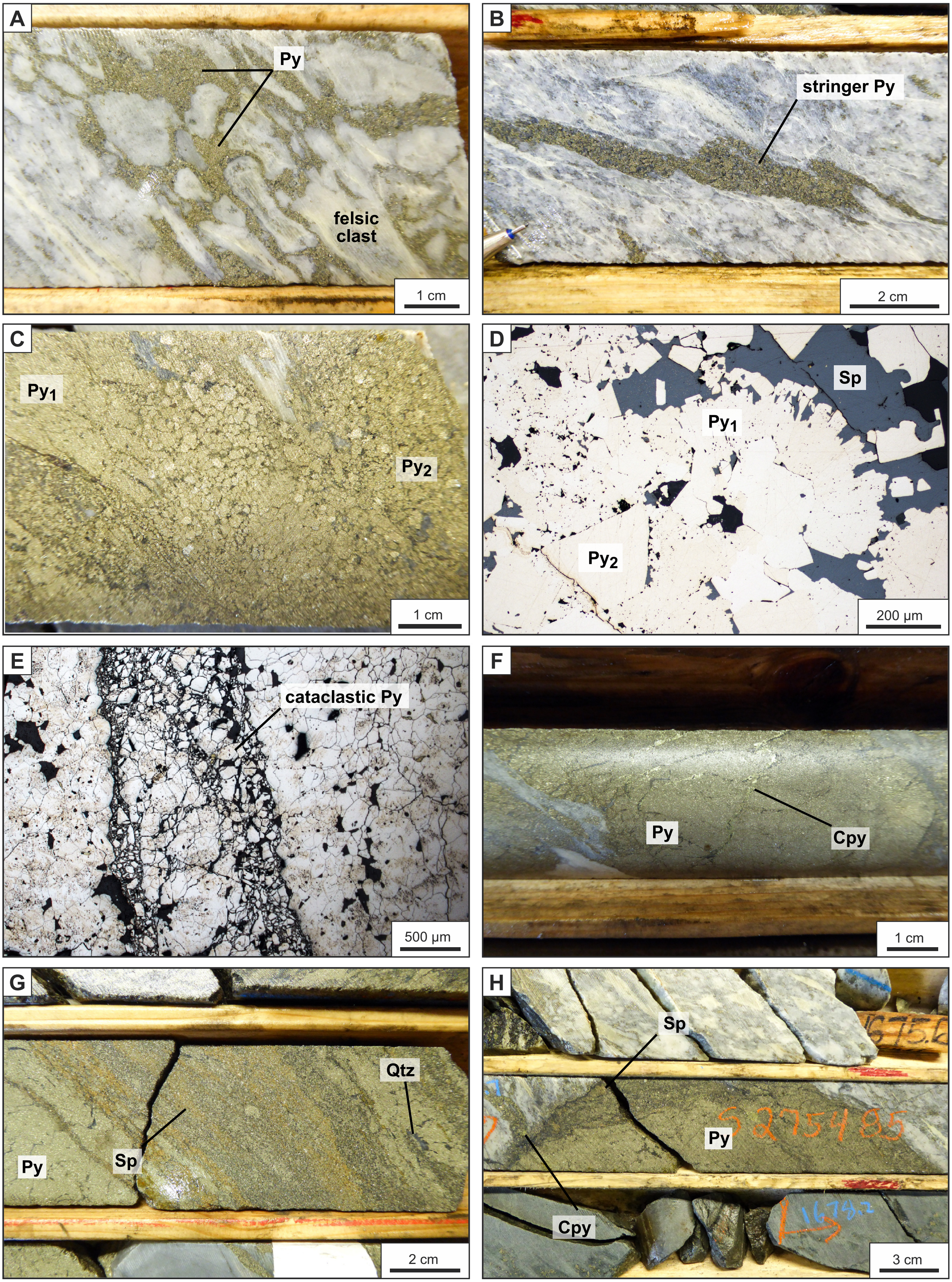
The original geometry of the deposit was likely modified by deformation (Krushnisky, 2018). Effects of the deformation on the deposit include shearing and transposition along the east-west foliation, subvertical stretching, with the long axis of the deposit oriented subparallel to the local stretching lineation, and strong east-west shearing and fragmentation of individual massive sulphide lenses (Sinclair, 1971).

Styles of Mineralization

The Horne 5 mineralized zones are composed of extensive zones of disseminated and stringer sulphides containing a series of stacked semi-massive (>30 vol.% sulphides) to massive (>70 vol.% sulphides) lenses. Massive sulphide fragments are present at several stratigraphic levels within the mineralized zones. The structural upper eastern part of the deposit hosts semi-massive to massive magnetite-chalcopyrite mineralization.

Disseminated and stringer mineralization are hosted in a matrix of felsic volcaniclastic rocks, on felsic clast margins, and along fractures and flow bands in synvolcanic felsic intrusions. Locally, partial replacement of felsic clasts occurs where mineralization is more abundant (Fig. 7a). Pyrite is the predominant sulphide, but minor amounts of sphalerite and chalcopyrite are also present locally. Sulphides show evidence of recrystallization and remobilization due to deformation and metamorphism, and sulphide stringers are often partially transposed into the main foliation (Fig. 7b).

Semi-massive to massive sulphide mineralization consists of fine-grained to locally coarser grained pyrite (Fig. 7c), sphalerite, chalcopyrite, and trace pyrrhotite, galena, stannite, cassiterite, and a variety of Au, Ag, and Pb tellurides (Krushnisky, 2018). A gradual increase in sulphides is observed towards massive sulphide lenses and strongly altered felsic clasts are often preserved within massive mineralization. Pyrite grains occasionally exhibit relict primary hydrothermal textures, including spheroidal and nodular textures, colloform textures (Fig. 7d), and spongy textures, as documented in younger, less deformed massive sulphides and modern seafloor deposits (e.g. Eldridge et al., 1983; de Ronde et al., 2011). Cataclastic pyrite is


A
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felsic clast
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C
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Py2
1 cm
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also commonly present (Fig. 7e) and results from post-depositional brittle deformation. Three subtypes of semi-massive to massive mineralization are distinguished based on mineralogy and metal content: 1) Cu-Au-rich massive pyrite-chalcopyrite (Fig. 7f), located predominantly in the structural eastern portion of the Horne 5 deposit; 2) Zn±Au-rich massive pyrite-sphalerite (Fig. 7g), found in the structural upper-western part of the deposit; and 3) Au-poor massive pyrite lenses present locally along the stratigraphic base of the mineralized zones.

Massive sulphide fragments (Fig. 7h) within the mineralized zones are characterized by mineralogy and geochemistry that show close similarities with the semi-massive to massive mineralization. Gold content of the sulphide fragments is generally elevated, with a mean of 3.2 g/t Au (Krushnisky, 2018; Krushnisky et al., in prep). These fragments are rounded to sub-rounded with sharp contacts and their distribution is stratiform, suggesting a clastic origin. They were likely sourced from sulphide lenses exposed on or near the paleo-seafloor by felsic mass flows, which incorporated them in the volcaniclastic rocks.

Semi-massive to massive magnetite-chalcopyrite mineralization consists of fine-grained magnetite in the matrix of felsic volcaniclastic rocks. Magnetite grains locally overprint and replace granoblastic pyrite. Chalcopyrite occurs interstitially within massive magnetite and as stringers along fractures. Areas with abundant magnetite-chalcopyrite mineralization generally display relative Au and Ag depletion and higher Cu grades (Krushnisky, 2018). This mineralization style is possibly associated with the intrusion of the Proterozoic diabase dykes that crosscut this area of the Horne 5 deposit and may be due to contact metamorphism, as was similarly demonstrated by Mookherjee and Suffel (1968) in the Upper and Lower H zones.

Trace Element Geochemistry and Distribution

The Horne 5 mineralized zones contain anomalously elevated values of Pb, Te, Cd, Sn, Hg, and In in addition to significant Au, Ag, Cu, and Zn grades. Statistical analyses show two principal metal assemblages: 1) Cu-Au-Te±Ag±Pb assemblage and 2) Zn-Cd-Sn-Hg-In±Au±Ag±Pb assemblage (Fig. 8). In the pyrite-chalcopyrite mineralization, trace elements, such as Au, Te, Ag and Pb, are concentrated in pyrite, either within its crystal structure and/or as inclusions of tellurides and electrum. Sphalerite is an important host for Cd, Hg, and In in the pyrite-sphalerite mineralization, whereas Ag and Pb are mainly hosted in galena and tellurides (cf. Cook et al., 2009; George et al., 2016).

At the deposit scale, Au, Ag, Cu, and Zn concentrations correlate well with sulphide abundance. Moreover, metal-rich semi-massive to massive mineralization is generally distributed along beds of coarse-grained and permeable volcaniclastic rocks, such as coarse lapilli tuff to tuff breccia units.

The Au distribution correlates relatively well with Cu-rich zones in the structural eastern portion of the deposit, especially at depths below 1200 m (Fig. 9). However, a few high-grade Au zones are not associated with significant Cu grades, such as a subvertical linear zone of Au enrichment stratigraphically overlying the western Zn-rich zones (Krushnisky, 2018). Local Au remobilization during east-west shearing towards low-strain sites is inferred from cross-sections of Au distribution (Fig. 9).

A relatively strong Cu-Zn zonation is present along strike of the deposit. The western part of the deposit is characterized by Zn±Au-rich pyrite-sphalerite mineralization, whereas the eastern portion is composed predominantly of Cu-Au-rich pyrite-chalcopyrite mineralization. A subtle Cu-Zn zonation is also present upwards from the footwall to the hanging wall of the deposit, with higher Cu grades distributed towards the stratigraphic base of the deposit and higher Zn grades towards the top of the deposit.

At the mineral scale, Au is concentrated in relict primary pyrite textures, such as spheroidal pyrite (Fig. 10). In relict primary pyrite, Au often occurs as lattice substitutions or as nano-sized particles, as indicated by relatively homogeneous laser-ablation inductively-coupled plasma mass spectrometry analytical signals (cf. Huston et al., 1995; Deditius et al., 2011). Gold correlates well with Te within relict primary pyrite,

Figure 7 opposite page. a) Disseminated pyrite (Py) mineralization preferentially developing in the matrix of felsic volcaniclastic rocks and partially replacing clast margins (ddh H5-15-07C, 1690.6 m). **b)** Partially transposed pyrite stringer within strongly altered felsic volcaniclastic rock located directly below a massive sulphide lens (ddh H5-15-07C, 1627.6 m). **c)** Fine-grained massive pyrite (Py_1) texture intermingled with coarser grained granoblastic pyrite (Py_2; ddh H5-15-07C, 1729.3 m). **d)** Photomicrograph (reflected light) of relict colloform pyrite texture showing radiating blades (Py_1) partially filled with massive sphalerite (Sp) and partially growing on euhedral pyrite porphyroblasts (Py_2, ddh H5-15-02, 1047.4 m). **e)** Photomicrograph (reflected light) of cataclastic pyrite showing strong brittle fragmentation of grains (ddh H5-15-01, 1159.4 m). **f)** Remobilized chalcopyrite (Cpy) along fractures in massive pyrite-chalcopyrite mineralization (ddh H5-15-08, 1535.2 m). **g)** Banded pale orange sphalerite with minor quartz (Qtz) gangue in massive pyrite-sphalerite mineralization (ddh H5-15-02, 1083.4 m). **h)** Round massive pyrite block with abundant pale orange sphalerite along the edges. Chalcopyrite is remobilized along a fracture in the felsic host rock (ddh H5-15-07C, 1676.7 m).

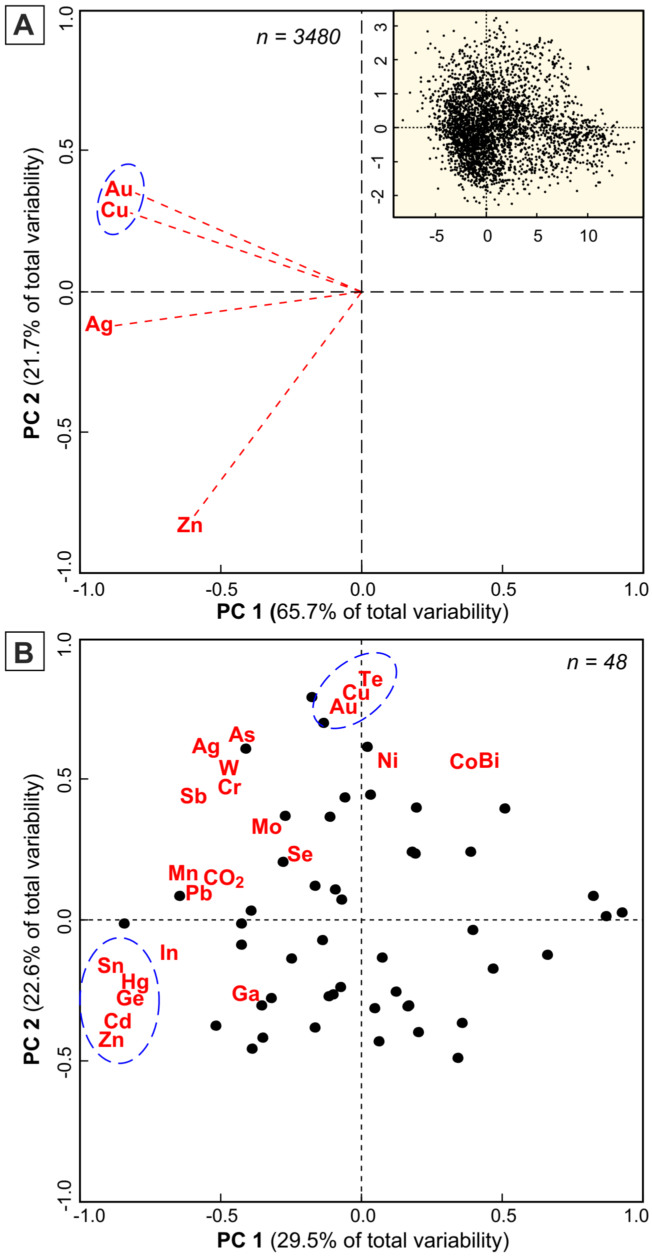

Figure 8. Principal component analyses performed in *R* programming language using the *rgr* package (Garrett, 2013). All data were standardized and transformed using a centred log ratio. **a)** Plot of the first and second principal components resulting from a robust principal components analysis (*gx.robmva.closed* function; minimum covariance determinant procedure) of Falco Resources Limited's historical database for Au, Ag, Cu, and Zn assays. Variables are shown in red and the individual data points are shown in the inset on a different scale. **b)** Plot of the first and second principal components (*gx.mva.closed* function) resulting from whole-rock geochemical analysis of most of the trace elements within the massive sulphide samples collected during this study. Variables (in red) and data points (black circles) are on the same scale and can be directly compared. Abbreviation: PC = principal component.

suggesting that these elements were transported in the same hydrothermal fluids that precipitated volcanogenic pyrite. In recrystallized pyrite, most trace

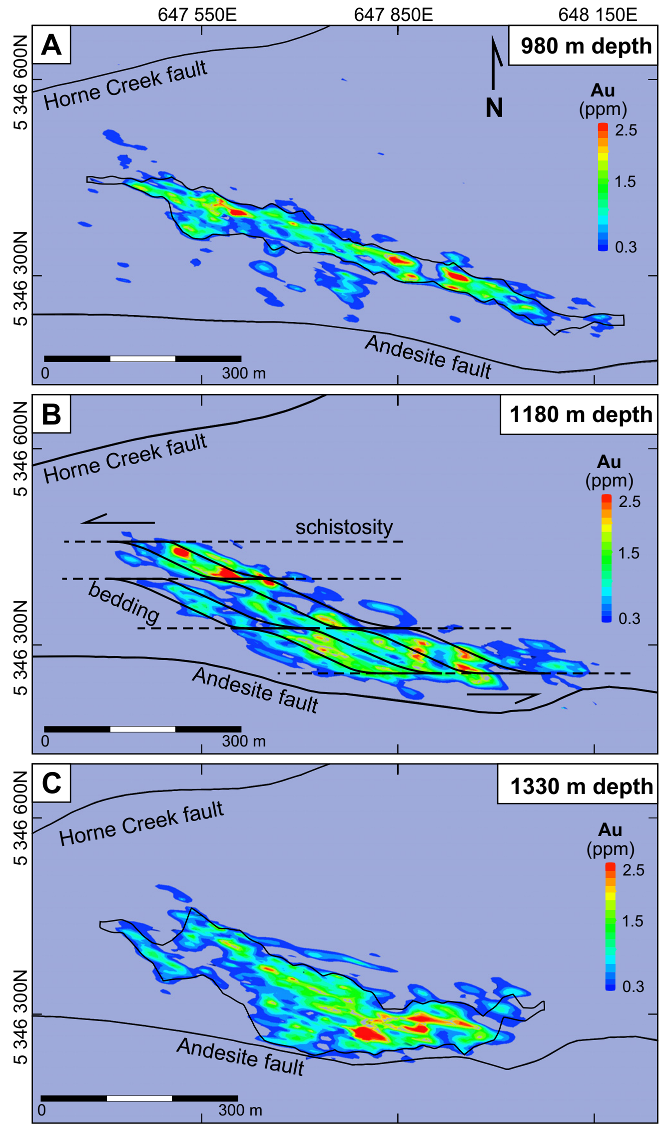

Figure 9. Sections of gold distribution in the Horne 5 deposit at **(a)** 980, **(b)** 1180, and **(c)** 1330 m depths. The outline of the Horne 5 mineralized envelope (≥0.5 g/t Au) is shown. Interpolations were performed in the *Leapfrog™* software. Interpolation parameters can be found in Appendix E of Krushnisky (2018).

elements occur as inclusions, such as galena, altaite, hessite, petzite and electrum, along grain boundaries, fractures, or in the surrounding silicates. Recrystallized pyrite contains very low trace element concentrations within its structure, except for elements such as As and Se (e.g. on the rim of spheroidal pyrite; Fig. 10).

DISCUSSION

This study provides several lines of evidence in favour of the synvolcanic nature of Au enrichment at the Horne 5 deposit. Gold deposition is interpreted to be contemporaneous to sulphide precipitation within a relatively large-scale VMS hydrothermal system. The presence of gold-enriched massive sulphide fragments in the mineralized zones indicates that early auriferous

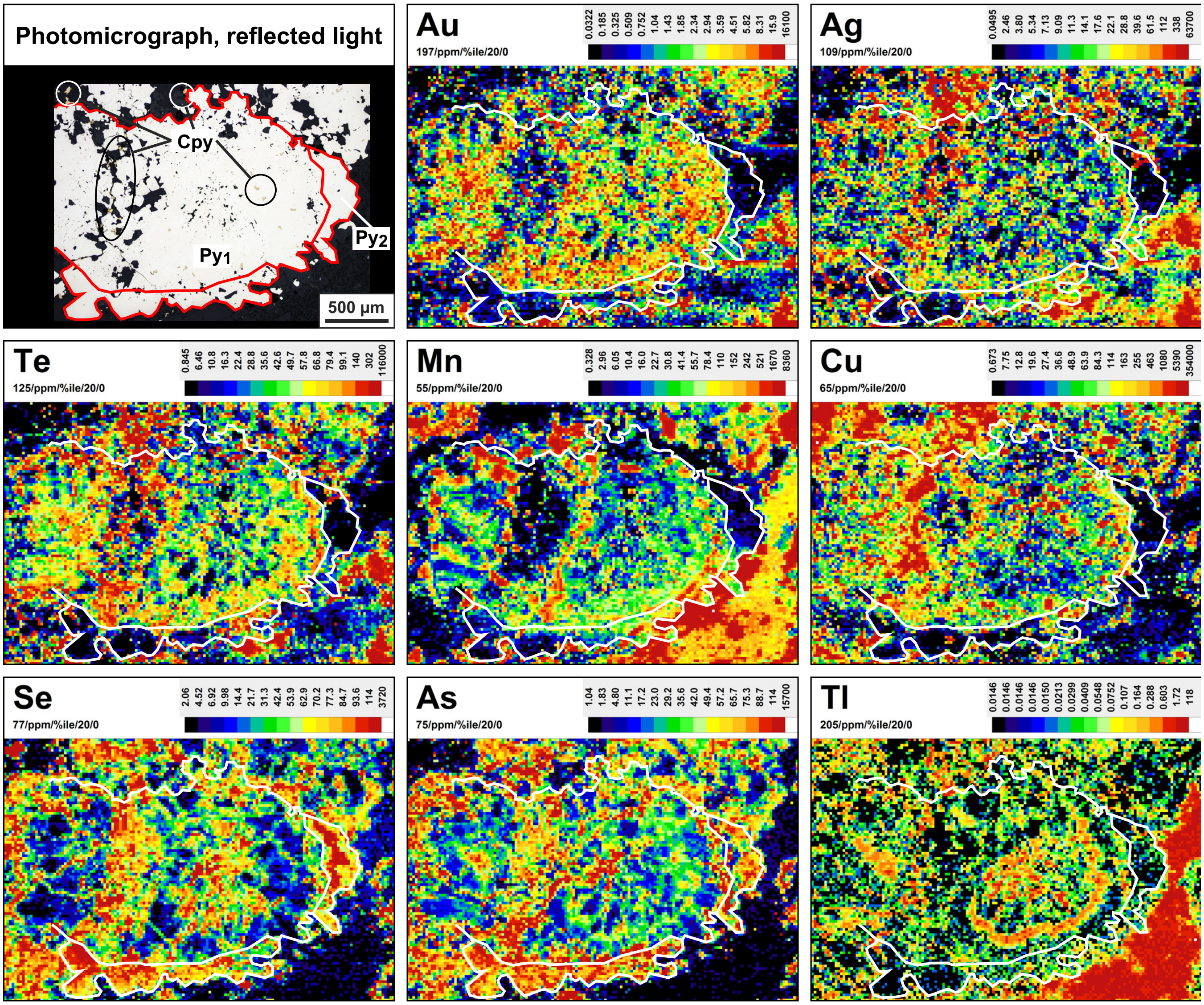

Figure 10. Laser ablation inductively-coupled plasma mass spectrometry compositional maps of spheroidal pyrite with a nodular texture (Py_1) rimmed by a metamorphic overgrowth (Py_2). Readers are referred to Lawley et al. (2015) for information on analytical methods.

sulphides were exposed at or near the seafloor and were eroded by mass flows during emplacement of the dacitic-rhyodacitic volcaniclastic rocks. Gold distribution at the deposit scale, which correlates well with the sulphide envelope, and its preferential association with partially preserved primary pyrite textures at the mineral scale also demonstrate that Au is synvolcanic. Furthermore, major fault zones in the immediate vicinity of the Horne 5 deposit contain no significant Au grades and are associated with alteration styles that contrast strongly with the synvolcanic alteration assemblages.

The distribution of Au and its associated trace elements (Te, Ag, Pb) is predominantly controlled by the variations in primary porosity and permeability of the host felsic volcaniclastic rocks. Gold and sulphide mineralization preferentially developed in the coarse-grained volcaniclastic rocks, which would have allowed for greater hydrothermal fluid circulation in the subseafloor environment. The presence of felsic syn-volcanic intrusions and fine-grained tuffs overlying some of the massive sulphide lenses suggests that they also controlled the distribution of the mineralization by acting as cap rocks to ascending hydrothermal fluids. Subseafloor precipitation of metals was likely an important process at Horne 5 by promoting fluid-rock interactions and reducing convective cooling as a result of the insulating effect of sulphide precipitation (Kerr and Gibson, 1993; Gibson et al., 1999; Doyle and Allen, 2003).

The Horne 5 deposit is characterized by a distinct metal zonation pattern. Zinc and its associated trace elements (Cd-Sn-Hg-In±Au±Ag±Pb) are distributed in the structural upper-western part of the deposit and a

Cu-Au-Te±Ag±Pb assemblage is concentrated in the eastern portion, at lower stratigraphic levels. Although modified by deformation and metamorphism, this zonation pattern reflects a primary architecture composed of distinct zones of Zn±Au and Cu-Au-rich mineralization, which likely formed under different physiochemical conditions. Zinc assemblages are typically associated with low-temperature hydrothermal fluids (100–200°C) which may have experienced extensive mixing with seawater, whereas the Cu-Au-rich zones likely represent higher temperature discharge sites (Large, 1977; Ohmoto, 1996).

Deformation and metamorphism at Horne 5 modified the geometry of the deposit, which was tilted, stretched, sheared, and transposed along the main schistosity. Gold remobilization appears to be very local in scale, with minimal redistribution along low-strain micro-structural sites. Similarly, ductile deformed minerals, such as chalcopyrite, are remobilized locally to fractures and pyrite grain boundaries. At the mineral scale, recrystallization of sulphide phases resulted in the expulsion of lattice-bound Au and its associated trace elements and local remobilization along fractures, inter-grain boundaries and the surrounding silicate gangue. Although Au-rich intervals are present along the margins of "syenite" dykes intruding into massive sulphide lenses of the Upper and Lower H zones, this is believed to be the result of deformation-induced Au remobilization (Kerr and Mason, 1990; Barrett et al., 1991; Gibson et al., 2000), as opposed to an orogenic gold overprint. This is further indicated by the absence of significant gold grades in the hematized felsic dykes (syenites) within the Horne 5 mineralized zones and the absence of Au-bearing deformation corridors.

The Horne 5 deposit presents both similarities and differences with the Upper and Lower H zones, in alteration styles, metal grades, mineralization styles, and sulphide mineralogy (Sinclair, 1971; Gibson et al., 2000). The similar host felsic volcaniclastic rocks and sericite-rich alteration styles suggest that the H zones and the Horne 5 deposit formed within the same broad hydrothermal system, which is also supported by a high Au to base metal ratio (2.6 for the H zones and 1.5 for Horne 5). Major differences in metal grades and mineralization styles, as well as the occurrence of strong chlorite alteration around the H orebodies, imply different physicochemical conditions of metal precipitation. Past studies suggested that the H orebodies and the Horne 5 deposit formed in different basins on the flank of a submarine volcanic complex (Kerr and Mason, 1990; Barrett et al., 1991; Cattalani et al., 1993; Kerr and Gibson, 1993; Gibson et al., 2000). The H orebodies presumably formed in a restricted basin that rapidly sealed itself from overlying seawater, facilitating the thermal evolution of the hydrothermal fluids and extensive zone refining of the sulphides which accounts for the pyrite-pyrrhotite-chalcopyrite assemblage and the very high Cu grades. The Horne 5 deposit likely formed in a larger, more open basin or depression, which allowed more seawater circulation in the permeable volcaniclastic rocks and thereby provided conditions that were favourable to the precipitation of a Au-rich pyrite-sphalerite-chalcopyrite assemblage. Additionally, since the Upper and Lower H zones appear to be separated by a fault (de Kemp et al., 2011), it is not unreasonable to assume that faulting brought the Lower H and Horne 5 zones in closer proximity during deformation.

In summary, this study indicates that the Au in the Horne 5 deposit is synvolcanic, making the Horne system (Upper and Lower H zones, plus Horne 5) one of the largest Au accumulations in the Abitibi greenstone belt, at approximately 16 Moz (~500 t) Au. It confirms the unique synvolcanic Au endowment of the southern Abitibi belt and strengthens previously proposed models inferring specific processes related to the early rifting of thickened arc - back-arc crust and formation of calc-alkaline felsic volcanic centres and Au-rich hydrothermal systems.

IMPLICATIONS FOR EXPLORATION

The Horne 5 deposit presents many interesting features that may be useful for exploration of synvolcanic Au in Archean terranes. Its stratigraphic setting, which is dominated by permeable felsic volcaniclastic rocks, demonstrates the potential of fragmental units to act as conduits for sulphide mineralization and hydrothermal fluid flow during VMS formation (Kerr and Gibson, 1993; Gibson et al., 1999; Doyle and Allen, 2003). The geochemical signature of the host felsic rocks constitutes another example of a large Au-VMS deposit associated with calc-alkaline felsic volcanic rocks. This highlights the importance of calc-alkaline felsic volcanic successions in volcano-sedimentary terranes such as the Abitibi greenstone belt when looking for VMS-Au mineralization (cf. Mercier-Langevin et al., 2011b).

The proximity of two major fault zones, the Horne Creek and the Andesite faults, to the Horne 5 deposit and textures attributed to deformation-induced Au remobilization share similarities with an orogenic Au overprint. The similarities between Au mineralization styles demonstrates the importance of conducting detailed mineralogical and geochemical studies of such deposits to accurately determine the principal controls on its distribution. This can strongly influence exploration models for deposit-scale exploration, as synvolcanic and orogenic Au deposits are characterized by different geometries, mineral assemblages, and Au deportments; attributes that are critical in determining the feasibility of a potential mineral prospect.

Compositional variations in alteration phases from the footwall to the hanging-wall of the Horne 5 mineralized zones, especially for white mica and epidote, can be a useful exploration vector for district-scale exploration.

Similarly, the footwall of the mineralized zones is associated with Mn-rich spessartine garnet and increases in Mn content in chlorite, carbonate, and massive sulphides. These features can be interesting exploration vectors pointing towards hydrothermal discharge sites, as was similarly documented at the LaRonde Penna deposit (Dubé et al., 2007).

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