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Targeted Geoscience Initiative 4: Contributions to the Understanding of Precambrian Lode Gold Deposits and Implications for Exploration

The Rainy River "atypical" Archean Au deposit, western Wabigoon Subprovince, Ontario

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ABSTRACT

The Rainy River project, located in the western Wabigoon Subprovince in western Ontario, is an advanced Au exploration project with an estimated 6.2 Moz Au and 14.6 Moz Ag in reserves and resources (New Gold Inc). The bulk of the Au and Ag mineralization occurs with pyrite, chalcopyrite, and sphalerite in disseminated ± stockwork form, and part of the ore is within quartz-sulphide-tourmaline-carbonate veinlets that are subparallel to the main east-trending, south-dipping penetrative foliation (S_2). Folded and transposed veins of quartz, Fe-carbonate, and tourmaline contain higher Au values, with Au in its native form or as electrum. At deposit-scale, there is a relatively good correlation between Au and Ag values, and between Au and Zn contents. Mineralization is concentrated in six zones that are elongated parallel to the main foliation. Higher grade zones are aligned within the main foliation plane along a stretching lineation (L_2) plunging to the southwest.

The deposit is hosted mainly within dacitic to rhyodacitic calc-alkaline volcanic domes, flows, and associated flow breccia. The rocks were regionally metamorphosed to greenschist facies. The proximal to immediate alteration consists of a sericite ±Fe-carbonate overprinted to various degrees by chlorite. Manganiferous garnet, chloritoid, and kyanite are present locally, in proximity to, or within, mineralized zones.

There is a strong correlation between the spatial distribution of the mineralization and the sericite-dominated alteration. Moreover, there is a direct correlation of stronger alteration intensity, higher-grade and/or more extensive mineralization, and host rocks of higher initial porosity (i.e. fragmental units), suggesting an early Au-Ag mineralization controlled by volcanism-related hydrothermal activity. Cross-cutting field relationships, preliminary laser-ablation inductively coupled plasma mass spectrometry analyses (LA-ICP-MS) of pyrite grains, and U/Pb ID-TIMS zircon geochronology further support the hypothesis of a synvolcanic origin for at least part of the Au mineralization. Subsequent deformation and metamorphism are responsible for transposition of the mineralized zones and metals within the main foliation plane and the associated stretching lineation, and for the modification of the primary alteration mineralogy to its greenschist-facies metamorphic equivalent.

INTRODUCTION

The Rainy River project is an advanced exploration project located in western Ontario. It has measured and indicated resources of 177 million tonnes at 1.09 g/t Au and 2.6 g/t Ag, for a total of 6.2 Moz Au and 14.6 Moz Ag (New Gold Inc. website). Combined open pit and underground operations are planned, with lower cut-off criteria of 0.3–0.45 g/t Au and 2.5 g/t Au. In contrast to many conventional mining operations for Archean Au mineralization, such as orogenic greenstone-hosted quartz-carbonate veins or Au-rich VMS deposits, the "atypical" Rainy River has a large bulk tonnage. Wartman (2011) interpreted the mineralization at Rainy River to be an Archean analogue of a low-sulphidation epithermal deposit, such as those present worldwide in Phanerozoic volcanic belts.

As part of a federal-provincial-academia-industry collaborative geoscience program (TGI-4 program, Lode Gold project: Dubé et al., 2011), the Rainy River project was initiated in 2013 to better document and

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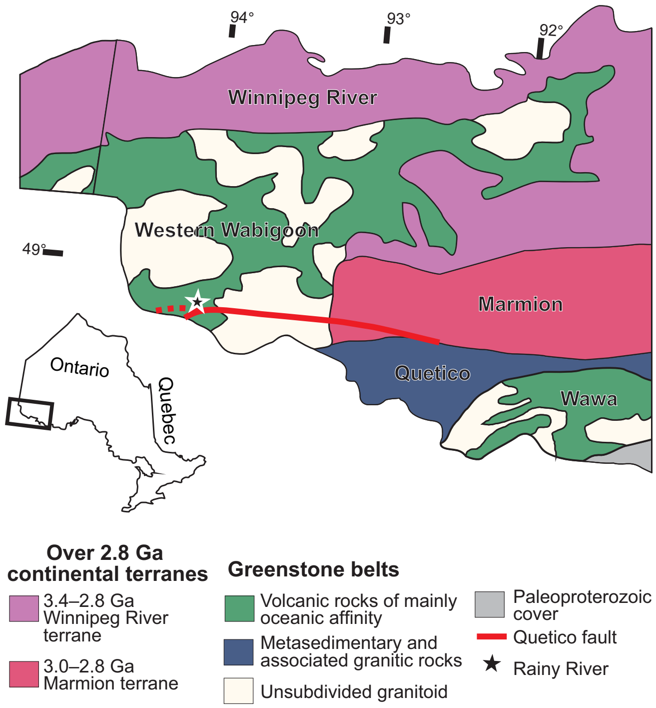


Figure 1. Regional geology of western Ontario, with emphasis on the western Wabigoon Subprovince. Adapted from (Percival, 2007).

characterize this atypical Au system. The specific objectives at Rainy River were to identify key primary and secondary controls on Au mineralization as well as vectors to ore, with the intent to improve and update the exploration model for large volcanic-hosted Au deposits in the Superior Province. The current study builds on previous work by Wartman (2011) and Wartman et al. (2013), who characterized the volcanic setting and hydrothermal alteration at deposit scale.

This report presents preliminary findings of host volcanic facies at Rainy River, the metamorphosed hydrothermal alteration assemblages, geometry, and composition of the mineralized zones, and the deformation-related features and effects. A brief discussion on the relative timing of Au-bearing events is also presented, based on preliminary interpretations. This work is part of an ongoing Master's project by the lead author, M. Pelletier.

DESCRIPTION OF THE RAINY RIVER DEPOSIT

Geological Setting

The Rainy River project is located in the Archean Rainy River greenstone belt in the southern part of the western Wabigoon Subprovince (Fig. 1). This subprovince is bounded to the north by Meso-Archean, greenschist-facies, plutonic Winnipeg River terrane and, to the south, by the metasedimentary, amphibolite-facies Quetico Subprovince (Fig. 1). The western Wabigoon Subprovince is greenstone-dominated, with

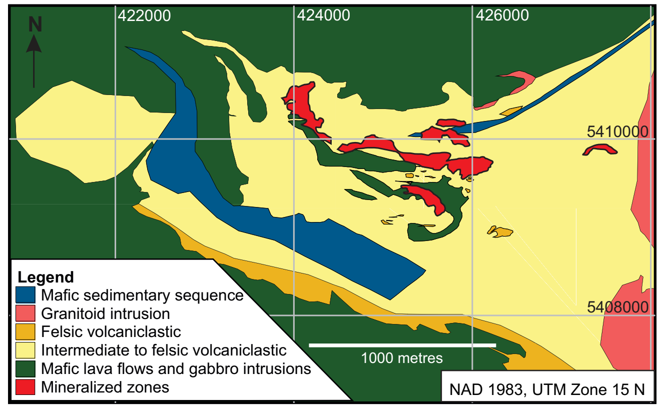


Figure 2. Geological map of the primary lithologies hosting the Rainy River deposit. Modified from a figure courtesy of New Gold Inc.

a restricted age span for submarine volcanism of 2745–2700 Ma (Percival et al., 2006) and with different geodynamic environments that include oceanic floor, plateau, island arc, and back-arc settings (Percival, 2007). Subsequent metaplutonic, mostly tonalitic rocks, crosscut the greenstone-dominated subprovince. Within the western part of the Wabigoon, structural elements reveal two major deformational events (D_1 and D_2), followed by late plutonism-related deformation (D_3) (Sanborn-Barrie, 1991; Percival et al., 2006; Percival, 2007).

On a local scale, the Rainy River project is located less than 5 km north of an east-trending fault, interpreted to be a splay of the domain-bounding Quetico fault (Fig. 1). This major fault is interpreted to be a subvertical shear zone with an overall dextral movement within a northwest-shortening transpressive regime (Davis et al., 1989; Fernández et al., 2013). The deposit is mainly hosted within an intermediate to felsic package, bounded to the north and south by mafic volcanic rocks of the Rainy River greenstone belt (Fig. 2). The Rainy River host sequence is cut by the Black Hawk quartz-monzonite stock located ~1–2 km east of the deposit (Wartman, 2011). The Black Hawk stock, which is affected by the main S_2 foliation, is dated at ca. 2698 Ma (New Gold Inc., unpublished data), whereas the volcanic rocks that host the Rainy River deposit are dated at approximately 2717 Ma (New Gold Inc., unpublished data). Greenschist-facies regional metamorphism affects all lithologies within the study area. Henceforth, the prefix "meta" is inferred in all succeeding descriptions. The area is characterized by up to 40 meters-thick glacial cover with very few exposed outcrops, especially proximal to the deposit area where information mostly comes from drill core.

Lithological Assemblages and Volcanic Facies

The Rainy River deposit is mainly hosted in felsic to

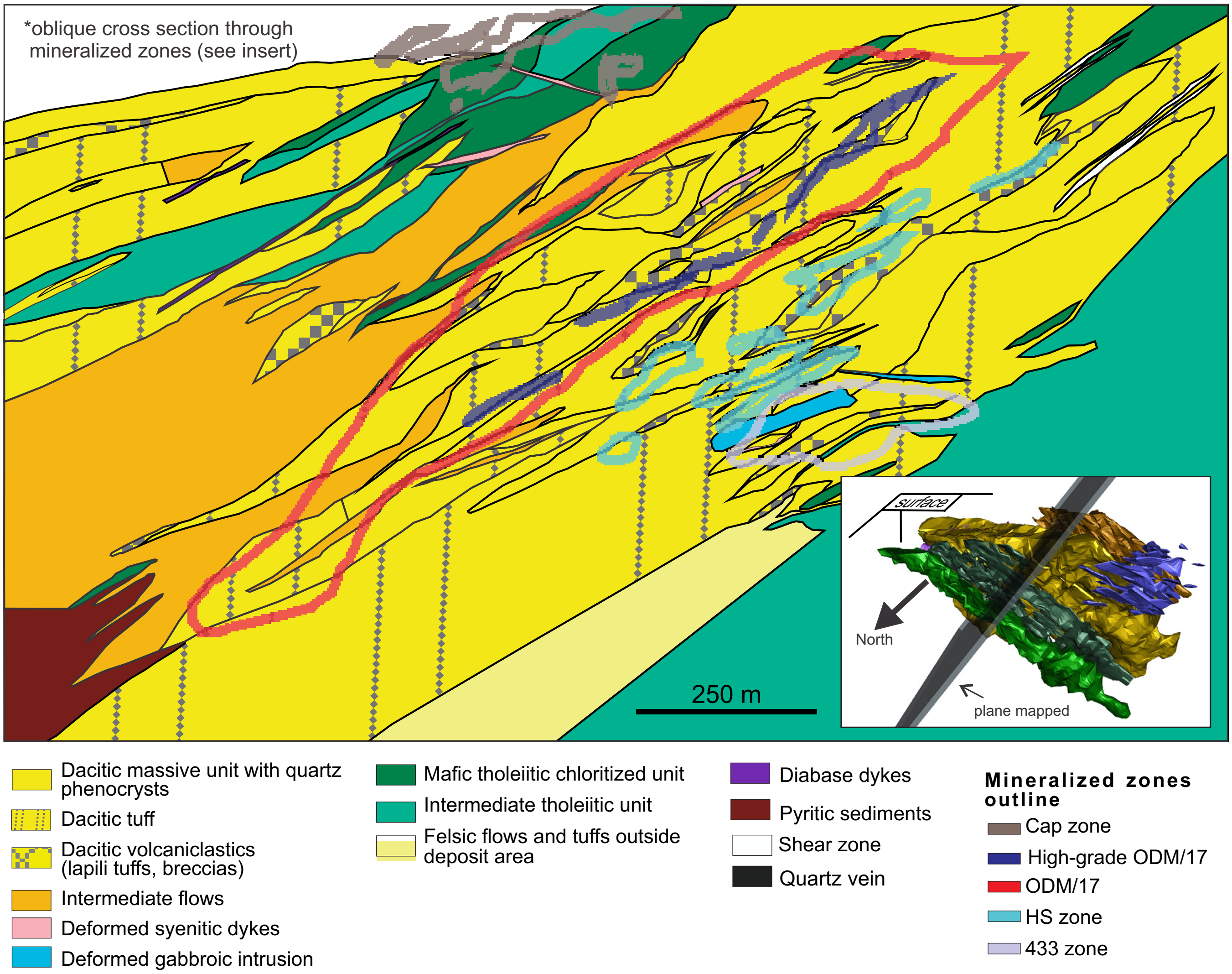


Figure 3. Preliminary geological map illustrating the distribution of the volcanic facies characterizing the dacitic units. This view represents an oblique section (323°/43°NE: Inset) that is perpendicular to the main foliation S_2 and stretching lineation L_2, both of which control mineralization. This map is based on drill-core observations and lithogeochemistry.

intermediate volcanic units in which, although overprinted by alteration and deformation of varying intensity, facies textures from massive (coherent) to volcaniclastic are still preserved (Wartman, 2011; Pelletier et al., 2014). Dacite and rhyodacite, which host the bulk of the deposit, have a distinct calc-alkaline affinity, though the basaltic to andesitic volcanic rocks, which bound the deposit to the north, west, and south (Figs. 2, 3), are of tholeiitic affinity (Wartman, 2011; Pelletier et al., 2014).

Outcrops of the structural footwall and hanging wall to the deposit were mapped in detail as part of this project and indicate an effusive intermediate to felsic volcanic environment of flows, domes, and associated volcaniclastic rocks (in situ and flow breccia) that formed in a subaqueous environment (Pelletier et al., 2014). An outcrop located in the structural footwall (north of the deposit) exposes well preserved flow bands (Fig. 4a) and transitional, curvilinear contacts between massive, amygdular flow units and monolithic to heterolithic, poorly sorted breccias (Fig. 4b). The breccia deposits contain disseminated, mostly matrix-controlled sulphide mineralization with anomalous Au values (0.1 g/t Au). These flows and associated breccias are also in sharp contact with pyrite-rich, mafic siliciclastic rocks. These sharp contacts are overprinted by the main S_2 foliation, indicating a pre main deformation control on their nature. The presence of flows and associated in situ flow breccia suggest a near-vent environment of deposition, whereas an outcrop mapped in the structural hanging wall (south of deposit) is characterized by a series of southward-younging, normally graded felsic tuff beds, possibly indicating a more distal position relative to the centre of effusive activity. On the same outcrop in the structural hanging wall, contact between the tuff beds and a porphyritic volcanic intrusion to the south is very irregular (Fig. 4c), characteristic of peperites that result

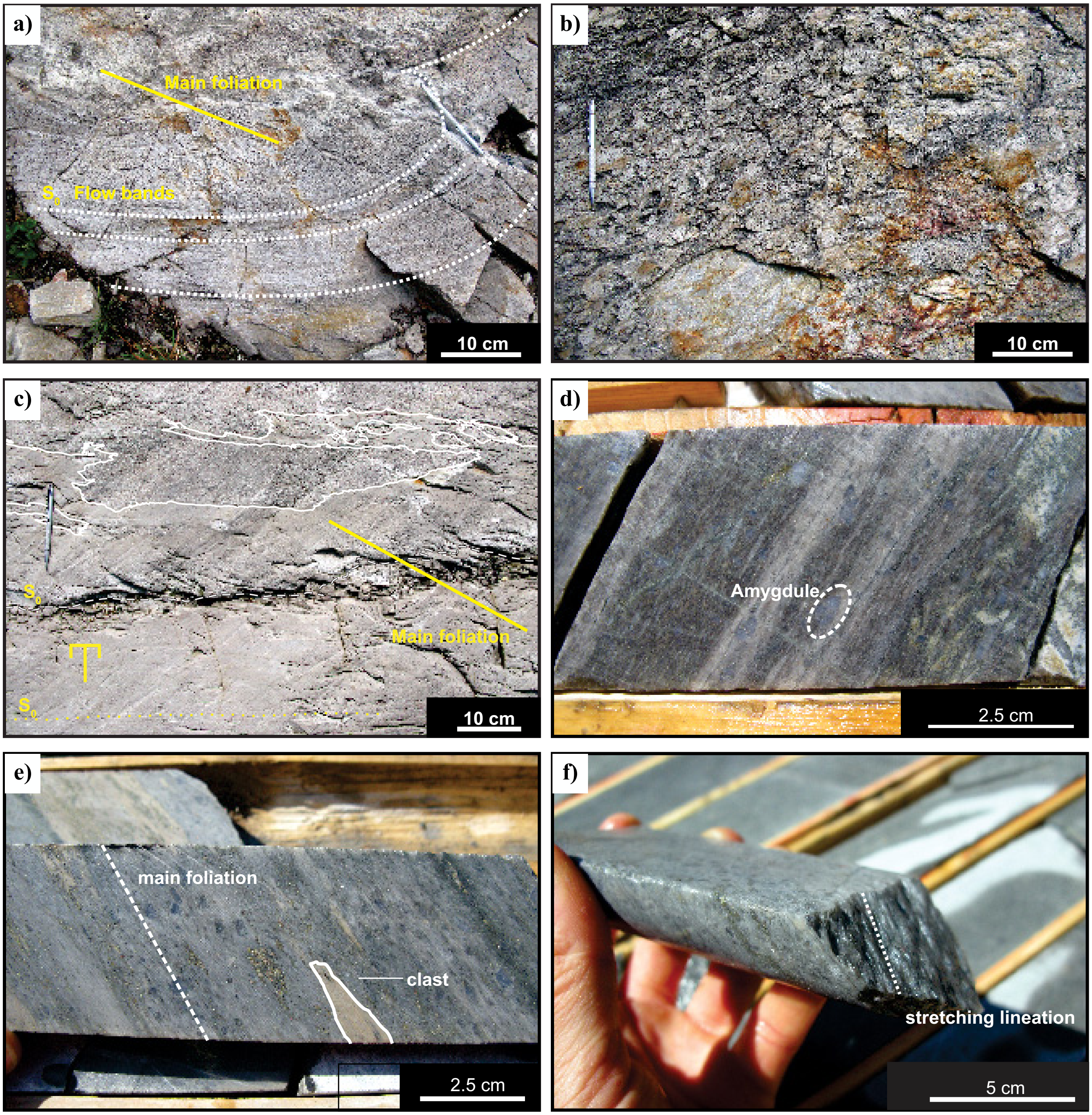


Figure 4. a) Flow bands (or flow foliations) in rhyodacite, with the main foliation (S_2) crosscutting the primary volcanic feature. **b)** Heterolithic, poorly sorted breccia with sulphide-bearing matrix and subangular clasts. **c)** Peperitic contact between a subaqueous synvolcanic sill or dyke (top of photo) and bedded tuff sequence (bottom of photo). **d)** Disseminated pyrite mineralization in a dacitic amygdular flow, with sericite and chlorite concentrated in millimetre- to centimetre-wide veinlets parallel to the main foliation plane. Sample from the ODM/17 zone. **e)** Disseminated granoblastic pyrite mineralization in heterolithic dacitic lapilli tuff from the HS zone. Clasts are flattened within the main foliation plane. **f)** Drill-core sample from the Cap zone structural hanging wall showing a well developed stretching lineation within the main foliation plane.

from the intrusion of lava into wet sediments (McPhie et al., 1993).

In addition to being noted in outcrop, primary volcanic textures were also observed in diamond-drill core (domes, lobes, and flow-breccia, e.g., Wartman, 2011; Pelletier et al., 2014). Massive felsic facies include aphanitic to strongly quartz ±plagioclase-phyric flow-banded lobes, amygdular flows, and flow breccia (Fig.4d) (Wartman et al., 2013; Pelletier et al., 2014). Primary plagioclase phenocrysts are only preserved in least-altered samples, and in all cases are partially replaced by sericite. Volcaniclastic rocks consist of fine-grained to lapilli-sized, mainly monolithic fragmental units where clasts are flattened and stretched along the main S_2 foliation plane (Fig. 4e). Overall, similar volcanic facies were mapped at surface in the hanging wall and footwall of the deposit and in drill core from the immediate vicinity of the deposit.

Outside the deposit area, mafic units of tholeiitic affinity are mostly massive, with occasional pillowed textures (Wartman, 2011), indicating a subaqueous depositional environment for the volcanic sequences that hosts and surrounds the Rainy River deposit. The southernmost mineralized zone of the deposit, the Cap zone, is hosted in mafic volcanics. Variably altered and mineralized tholeiitic basalt intercalated with altered and mineralized dacitic to rhyodacitic flows are present in that area.

Deformation

Tectonic models generally regard the western Wabigoon as an oceanic terrane accreted to the Winnipeg River terrane during the Central Superior orogeny (Melnyk et al., 2006). This horizontal shortening event (D_1) generated north-trending upright F_1 folds. A subsequent deformation event (D_2) initiated transcurrent fault zones at the Quetico – western Wabigoon boundary, where the Rainy River project is located, resulting in a penetrative east-striking S_2 schistosity overprinting the D_1-related folds (Sanborn-Barrie, 1991; Percival et al., 2006). This steeply dipping S_2 foliation is the main penetrative fabric observed in the belt. Rare S_3 structures have been observed associated with the emplacement of relatively late intrusions (Sanborn-Barrie, 1991).

Up to five deformation events have been defined in the study area (e.g. Rankin, 2013). The main penetrative foliation, herein referred to as S_2, is oriented at 102°/51°SSW and is present in outcrop, diamond-drill core, and in thin section, (Figs. 4a, e). No clear evidence of an earlier tectonic fabric is present (or preserved) in the study area. A well developed stretching lineation (L_2: 225°/55°) is associated with the main S_2 foliation (Fig. 4f). This foliation is thought to result from a major north-south compression (Hrabi and Voss, 2010), or from an early east-verging thrusting and folding event superimposed by north-south shortening and east-southeast-trending upright folds (Rankin, 2013). The S_2 foliation and associated L_2 lineation have a strong influence on the current geometry of the mineralized zones.

The main S_2 foliation is characterized by discrete to extensive bands of aligned sericite ±chlorite, anastomosing around less altered clasts in volcaniclastic units. Deformation intensity is mostly dependent on alteration intensity; hence the presence of high-strain corridors focused in intensely altered rocks. Weakly

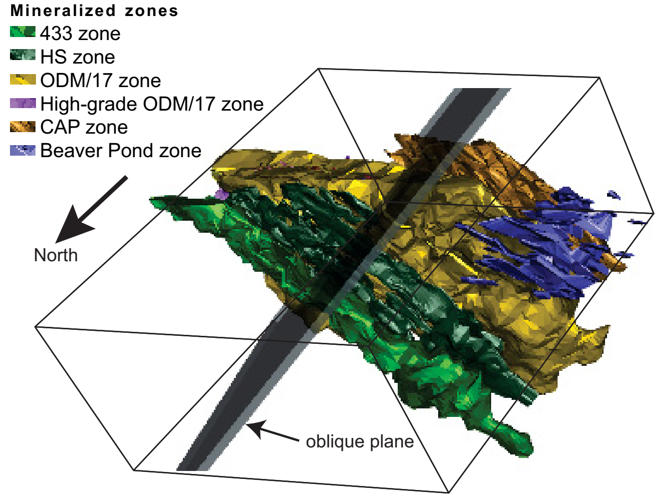


Figure 5. Three-dimensional view of the mineralized zones comprising the Rainy River deposit, with the oblique plane crosscutting the main mineralized zones at the predicted open-pit mining depth and perpendicular to the measured stretching lineation (L_2). View is looking east-southeast (mineralized zones dip 55° towards 192°N). Modified from a figure courtesy of New Gold Inc.

developed interpreted C-S fabric (in unoriented drill core) is developed in areas of greater deformation, mainly within the HS zone. Late kink bands are common in the immediate hanging wall of the ODM zone.

Brittle fractures with a sinistral movement, oriented at 195°/75°NW, crosscut the main fabric and are present in both drill core (unoriented) and outcrop. This late deformation offsets the mineralized zones at the metre scale, but does not seem to have generated any remobilization.

Mineralized Zones

Mineralization is distributed within a series of four main zones, which are, from north to south, the 433, HS, ODM/17, and Cap zones (Figs. 2, 5). They occur in a series of stacked bodies, all subparallel to the main east-west-trending, moderately south-dipping S_2 foliation (102°/51°SSW) (Figs. 2, 5). High-grade ore shoots within these zones are elongated subparallel to a southwest-plunging lineation (225°/55°) and contained within the main foliation plane. In addition, the Beaver Pond and Intrepid zones are satellites to the four main mineralized zones, flanking the ODM/17 zone respectively to the east and west.

The ODM/17, HS, and 433 zones are hosted by calc-alkaline dacite flows, tuffs and lapilli tuffs. The largest and richest mineralized zone on the Rainy River project is the ODM/17 zone; it is continuous over 1000 m along strike, can be up to 250 m thick, and extends from surface to a depth of ≥1000 m (Figs. 2, 3, 5). The HS zone defines a discontinuous, mainly low-grade zone with overprinting chlorite and an overall higher degree of sericitization and strain than the ODM/17

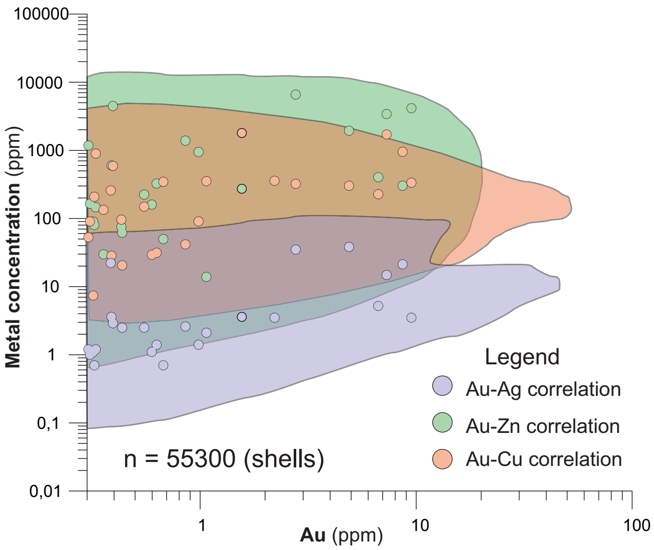


Figure 6. Scatter plot showing the correlation between Au (100 ppm > Au ≥0.3 ppm only) and Ag, Zn, and Cu. Data from New Gold inc. (n = 55,300) and this study (n = 27).

zone. Mineralization in the 433 zone is generally of higher grade than the ODM/17 zone, and has a more continuous and homogenous shape than the HS zone. The Cap zone is the only ore zone that is mainly hosted in tholeiitic basaltic-andesitic rocks.

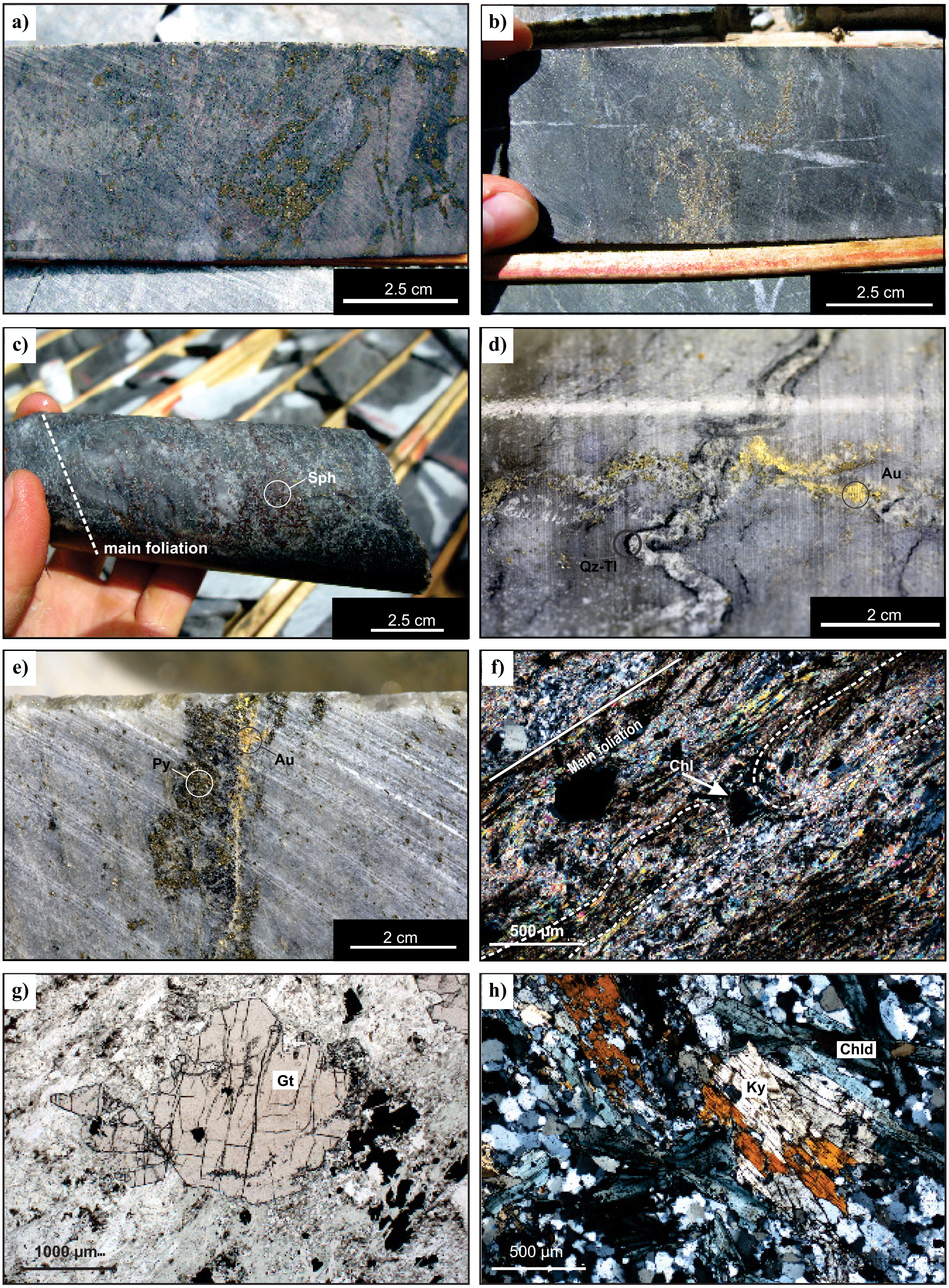
The Rainy River deposit is characterized by a strong Au and Ag endowment in comparison to its base metal content. At the deposit scale, Au shows good affinity with Cu, Ag, and, to a lesser extent, Zn (Fig. 6). Zinc content greater than 0.7 ppm and/or Cu values greater than 3 ppm in the host rock are good indicators of the presence of Au and Ag.

The main Au zones are characterized by abundant disseminated auriferous pyrite (≤10 vol.%) and lesser sphalerite. Pyrite is flattened in the main S_2 foliation plane and it is commonly granoblastic (Figs. 4e, 7a, b, 8). Pyrite crystals are commonly characterized by complex zoning, usually with an early, inclusion-rich core and a later inclusion-free corona. The latter is probably the result of metamorphic recrystallization. Inclusions in pyrite consist primarily of chalcopyrite, which is also observed filling fractures in pyrite grains. This chalcopyrite fracture-filling is interpreted as late remobilization in low-strain zones (Fig. 8). A long list of trace elements is preferentially associated with the early pyrite phase (e.g. Cu, Zn, As, Ag, In, Sn Sb, Au, Pb: Fig. 8), whereas the recrystallized part has much lower trace element contents, usually with distinct Ni, Co, and Bi growth zones (Fig. 8).

Within the 4 main zones, Au and Ag also occur in pyrite-sphalerite-chalcopyrite±galena veinlets and veins, which are subparallel to the main S_2 foliation plane (Fig. 7c). Generally, these veinlets and veins are associated with higher precious metal values than the disseminated auriferous pyrite. The sphalerite in these veinlets varies in colour, but is generally yellowish, suggesting a high Zn/Fe ratio. In thin section, these polymetallic veinlets show a zonation with sulphides of lower ductility systematically rimmed by sulphides of increasing ductility; i.e., pyrite cores are successively rimmed by sphalerite, chalcopyrite, and finally galena. This zonation, based on variations in physical properties, is interpreted to be the result of partial remobilization during the main deformation and metamorphism event that affected the area.

Electrum, with variable Au content, is locally present within the main orebody (ODM/17 zone), especially in less than 100 m-wide, high-grade cigar-shaped zones oriented parallel to the stretching lineation and flattened within the main S_2 foliation plane (see the high-grade ODM/17 zone in Figs. 3, 5). It occurs in deformed sulphide-bearing veinlets and in folded quartz-Fe carbonate-tourmaline veins (Fig. 7d). These veinlets and veins are transposed within the main foliation plane, suggesting that they formed pre- to syn-main deformation. Furthermore, some diamond-drill core intercepts contain deformed electrum-bearing sulphide veins, which are crosscut by later deformed quartz-tourmaline veins (Fig. 7d). This basic crosscutting relationship suggests an early, pre-main-phase deformation, Au-precipitation event in host rocks that have undergone polyphase deformation. Such an interpretation is in agreement with the trace element distribution in the early pyrite. Gold-rich electrum is also present in brittle fractures (Fig. 7e), which is interpreted as the result of late, local remobilization of Au.

Figure 7 (opposite page). a) Ultrafine rutile dusting (pinkish hue) in tholeiitic-affinity andesite with granoblastic pyrite mineralization associated with deformed chlorite veins. Sample from the 433 zone. **b)** Deformed pyrite, sphalerite, and carbonate veinlets from the tholeiitic-affinity basalt of the Cap zone. **c)** Sphalerite, chalcopyrite, and galena stockwork veinlets flattened and transposed within the main foliation plane and associated with a deformed quartz-calcite-chlorite vein. Sample from the ODM/17 zone. **d)** Early, Au-bearing, deformed veinlet crosscut by a later quartz-tourmaline vein, which is also deformed, demonstrating an early gold-mineralization event followed by at least two deformation events. **e)** Visible gold locally remobilized within a late brittle fracture. **f)** Photomicrograph of a sericite-altered rhyodacitic lapilli tuff showing a pervasive foliation affecting white mica grains, with coarser grained chlorite overprinting the fabric. **g)** Photomicrograph of a spessartine garnet (25–28 wt% MnO) in a chlorite-sericite matrix. Sample from the ODM/17 zone. **h)** Photomicrograph of chloritoid minerals with bowtie texture and kyanite grains from the aluminosilicate-rich alteration zone within the ODM/17 mineralized body. Abbreviations: Au = gold, Chl = chlorite, Chld = chloritoid, Ky = kyanite, Py = pyrite, Qz = quartz, Sph = sphalerite, Tl = tourmaline.


a)
2.5 cm
b)
2.5 cm
c)
Sph
main foliation
2.5 cm
d)
Au
Qz-Tl
2 cm
e)
Py
Au
2 cm
f)
Main foliation
Chl
500 µm
g)
Gt
1000 µm
h)
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Ky
500 µm

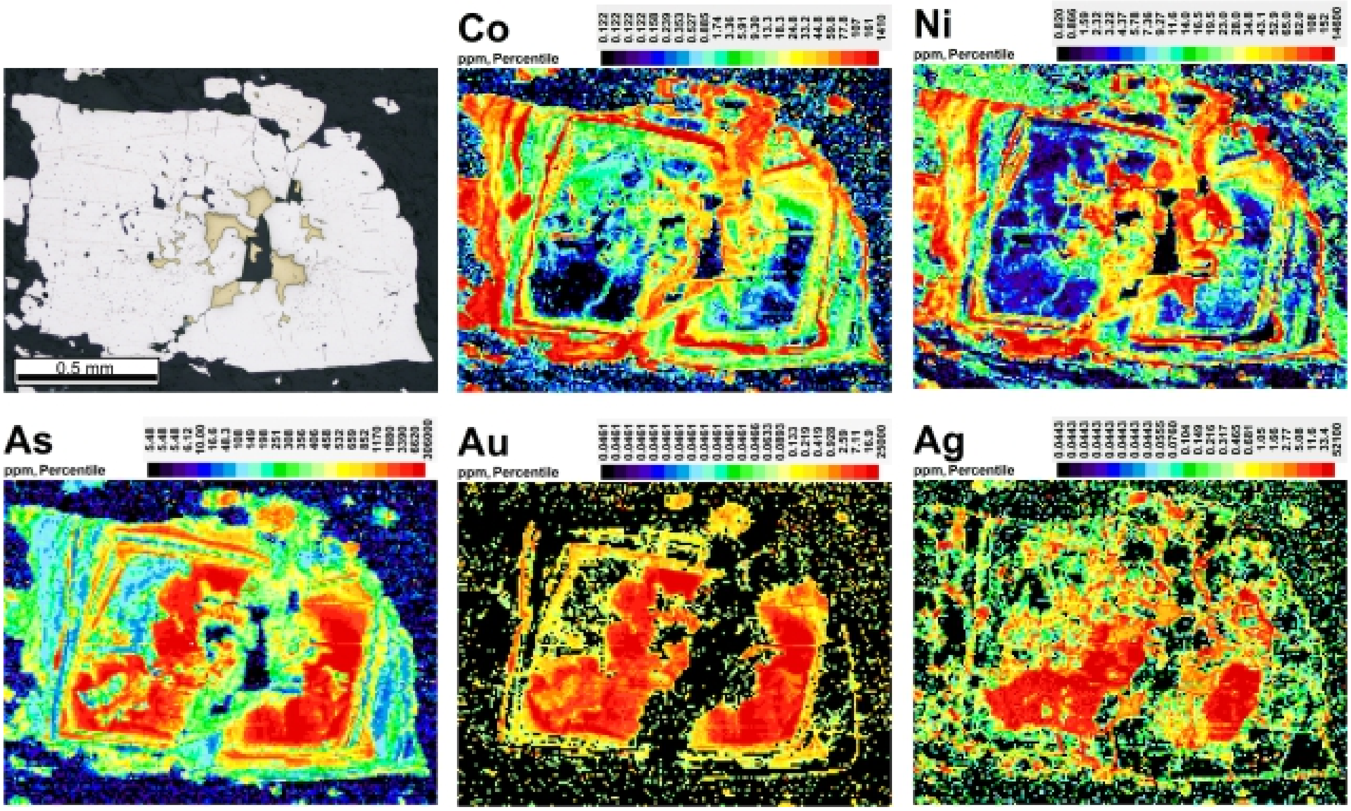

Figure 8. LA-ICP-MS element concentration maps (ppm) of a partly recrystallized pyrite grain from the ODM zone.

Alteration

The metamorphosed hydrothermal alteration assemblages associated with the Rainy River deposit were first described by Wartman (2011). Additional mineral phases have been documented in the current study, including kyanite and chloritoid, which suggests possible local zones of pre-metamorphism, advanced argillic-style alteration. When plotted on an alteration box plot (Large et al., 2001), the samples follow trends typical of VMS-related hydrothermal systems (Fig. 9). Most mineralized, calc-alkaline affinity samples (Fig. 9: represented by a star symbol), are located near the most altered ends of the muscovite, sericite+chlorite+pyrite, and sericite trends, and the most mineralized, tholeiitic affinity samples trend towards the ankerite and chlorite poles (Fig. 9).

Sericite Alteration

Sericite is ubiquitous throughout the deposit and represents the principal alteration mineral. Preliminary electron microprobe analyses indicate that most white mica (sericite) consists of muscovite. The sericite-dominated alteration seems to be better developed in volcaniclastic facies within the host dacite complex, suggesting a distribution controlled by primary composition of the protolith and porosity in the host rocks. Furthermore, drill core indicates that the spatial extent of the main mineralized body (ODM/17) is correlated with the spa-

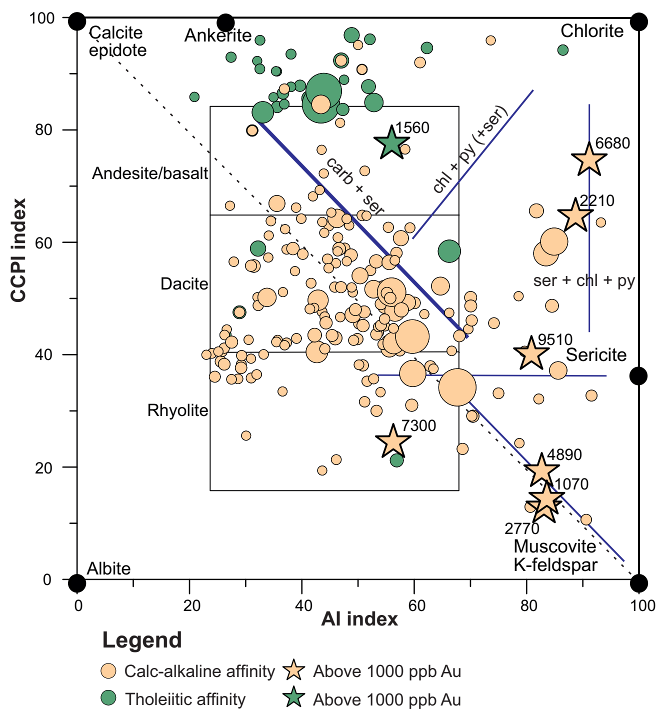

Figure 9. Alteration box plot (Large et al., 2001) with samples (n = 233) from this study sorted according to their magmatic affinity. Circle sizes are proportional to the Au content from 0 to 1 ppm. Ishikawa alteration index (AI) = $100(K_2O+MgO))/(K_2O+MgO+Na_2O+CaO)$. Chlorite-carbonate-pyrite index (CCPI) = $100(Mg+FeO)/(MgO+FeO+Na_2O+K_2O)$.

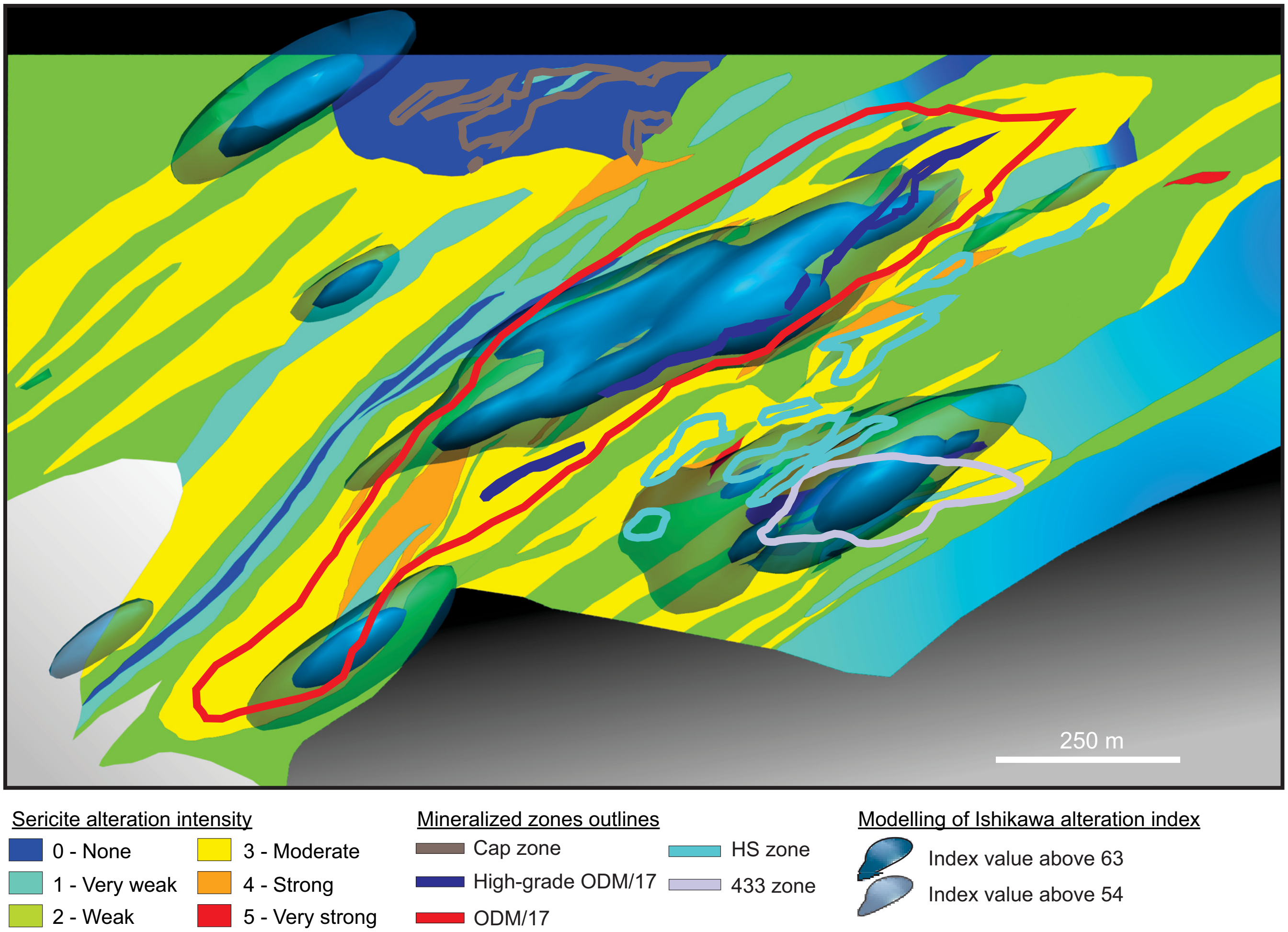

Figure 10. Implicit 3-D model of the distribution in space and intensity of the Ishikawa alteration index (AI = 100(K_2O+MgO))/(K_2O+MgO+Na_2O+CaO) plotted on the sericite-alteration intensity oblique map generated from visual observations of drill-core intercepts. This oblique plane is oriented 323°/43°NE and perpendicularly crosscuts the stretching lineation measured within the deposit. The outline of the main mineralized zones is also traced on the map. Implicit modelling was made with Leapfrog Mining© software (version 2.5.3.61) using lithogeochemical data from drill-core samples. It is constrained by the main stretching lineation trend (225°/55°). The outer shells correspond to a cut-off AI value of 54, the highest grade shell to a value of 63.

tial extent of a zone of well developed, pervasive to texturally destructive sericite alteration in the host dacite (Fig. 10), underpinning the role of hydrothermal processes in the generation of mineralized zones.

In the coherent dacite (lobes and/or domes), sericitization occurs as sparse to abundant bands and veinlets, with mica grains defining the main S_2 foliation plane (Fig. 7f). In addition, sericite partially to completely replaces relict feldspar phenocrysts. Fragmental facies composed of breccia and tuff show a similar distribution of sericite minerals, with the particularity of having sericite bands wrapping around more competent lapilli and clasts (Fig. 4e). In other cases where the lapilli and clasts were more prone to alteration, they are entirely replaced by sericite.

An implicit 3-D model of the distribution and intensity of the alteration index (AI = 100*(K_2O+MgO)/(K_2O+MgO+Na_2O+CaO: Ishikawa et al., 1976) was generated with Leapfrog Mining© software (version 2.5.3.61) using lithogeochemical data from drill-core samples (Fig. 10). Constrained by the main stretching lineation trend, this model further demonstrates the correlation between the main mineralized zones hosted in dacite and a zone with high AI values, plausibly caused by major replacement of volcanic glass and sodic plagioclase by sericite and chlorite.

Chlorite Alteration

Chlorite is the second most common mineral present in the alteration zones at the Rainy River deposit (Wartman, 2011). It is commonly associated with disseminated pyrite and quartz-carbonate veins and its abundance varies between 1 and 10% of the host rock, unlike sericite that can compose up to 65% of the rock. Chlorite can be observed rimming disseminated pyrite grains, or in very fine (≤1 mm) veinlets and rare ≤1 cm veins, both parallel to the main S_2 foliation. Replacement of relict feldspar phenocrysts with unoriented chlorite grains is locally present. Chlorite is generally coarser than sericite and tends to overprint an apparently earlier, more pervasive, sericite alteration (Fig. 7f). Chlorite distribution extends to most of the deposit, without displaying any specific zonation. Preliminary electron microprobe data reveal an Mg-rich tendency for chlorite throughout the deposit, with an additional population of Fe-rich chlorite restricted to the mafic rocks.

Sericite-Carbonate Alteration

Located within the ODM/17 zone is an area of sericite-carbonate alteration. Although this alteration assemblage is present elsewhere in the deposit, it is most continuous and strongest within the dacite-hosted main mineralized body. Chlorite is rare to absent in this alteration assemblage. The sericite-carbonate alteration is restricted to mineralized areas of the deposit and as such is commonly associated with veinlets or dissemination of pyrite, sphalerite, and chalcopyrite. Carbonate minerals are mainly Fe- to Mg-rich, although further work is underway to investigate a potential spatial zonation. Carbonate occurs as blebs or grains disseminated in the matrix, as very fine veinlets and, less commonly, as folded veins. In all cases, these carbonate is transposed within the main foliation plane.

Manganese-Rich Garnet Zone

Manganiferous garnet (spessartine: $Mn_3Al_2(SiO_4)_3$) is found sporadically as discontinuous small zones within dacite of the ODM/17, but mostly in a sliver-shaped zone in the immediate structural hanging wall of the ODM/17 zone (Fig. 7g). The garnet grains have a relatively homogenous major element composition and individual grains do not exceed 5 mm in size. The spessartine garnet zone is sericite- and chlorite-bearing, and garnet does not exceed 2 vol.% of the rock.

Kyanite-Chloritoid Zone

Slivers of kyanite, chloritoid and quartz, which are less than 25 m long and 2 m wide, occur within the ODM/17 zone. This assemblage, although well preserved, is very fine-grained (Fig. 7h). In other Archean synvolcanic (e.g. Headway-Coulee prospect: Osterberg et al., 1987) and hydrothermal-related deposits, such aluminosilicate zones, are interpreted as a metamorphic analogue to modern-day advanced argillic alteration assemblages found in hydrothermal activity zones characterized by low-pH fluids (e.g. Bousquet 2-Dumagami and LaRonde Penna Au-rich VMS deposit: Dubé et al., 2007b, 2014; Mercier-Langevin et al., 2007).

Rutile Zone

A <40 m-wide zone, located between the HS and 433 zones, is characterized by a very fine and pervasive rutile dusting. More patchy intervals are also present within the 433 zone associated with boudinaged pyrite, chalcopyrite, and chlorite veins that are folded and transposed within the main foliation (Fig. 7a). These rutile-altered rocks display a characteristic orange to pink hue, which is easily identified when logging (Fig. 7a). Rutile and titanite also occur in trace amounts in the dacite host rocks of the ODM/17 zone and can only be observed in thin section. Further work is underway to characterize the spatial distribution of these titanium oxides within the main mineralized body.

U-Pb Zircon Geochronology

Four samples were collected for high-precision U-Pb ID-TIMS zircon geochronology to further constrain the timing of magmatic and hydrothermal events. Samples from the host dacite and intrusive rocks were collected, as well as samples from an unaltered but deformed dyke that cuts the mineralization in the 433 zone. Preliminary results gave back an age of 2693 Ma for the dyke and 2716 Ma for the host dacite, constraining the main deformation to between >2716 and 2693 Ma, and the mineralization to >2693 Ma. These results also indicate that the host succession was emplaced at approximately 2716 Ma (including synvolcanic intrusions). More work is underway to refine these ages and the implications for the timing of events at Rainy River.

DISCUSSION

The Rainy River deposit is hosted in a calc-alkaline dacite to rhyodacite complex, bounded by geochemically distinct tholeiitic, intermediate to mafic volcanic and associated siliciclastic rocks of the western Wabigoon Subprovince. The current geometry of the mineralized zones is largely controlled by the main S_2 foliation and associated L_2 stretching lineation, but the presence of mineralization seems to be attributed to a pre-main-phase deformation fertile hydrothermal system. This is supported by a semi-conformable pervasive sericite-dominated alteration assemblage preferentially developed in fragmental rocks around the main ODM/17 mineralized zone, independent of strain distribution at property scale. However, with a stacking of relatively thick ore zones within a relatively compact felsic-intermediate volcanic centre, the geometry of the entire deposit does not appear to be solely controlled by the main deformation. Gold mineralization concentrated in primary generations of pyrite also reinforces the scenario of an early origin for at least part of the Au at the Rainy River deposit. Uranium-Pb geochronology results and crosscutting relationships are in agreement with an early hydrothermal system (≤2716 Ma and ≥2693 Ma). This interpretation is also in agreement with previous studies that interpret the Rainy River deposit as a syngenetic Au system (i.e. low-sulphidation epithermal-style system: Wartman, 2011; Wartman et al., 2013). However, all evidence suggests that the deposit was formed in a subaqueous setting, and the bulk of the mineralization consists of disseminated pyrite ±sphalerite in a very large sericite-dominated alteration halo rather than an organized colloform-crustiform low-sulphidation-style vein system with fracture-controlled alteration, as would be expected for a low-sulphidation deposit *sensu stricto*. It is premature to propose a specific genetic model, but current work and geological features suggest that the Rainy River deposit is an atypical, pre-main-phase deformation Au deposit formed by a hydrothermal system similar to the ones involved in other known Archean VMS systems (e.g. LaRonde Penna, Westwood, Bousquet 1 deposits). There are possible analogues to Rainy River elsewhere in the Wabigoon Subprovince (e.g. Headway-Coulee prospect) and in the Superior Province (e.g. Bousquet district).

IMPLICATIONS FOR EXPLORATION

The specific characteristics of the 6 Moz Au, "atypical" bulk-tonnage Au mineralization at the Rainy River should be included in updated exploration model for Au deposits in the Superior Province. The updates to the exploration model would include incorporating geological characteristics and signatures previously documented for Archean Au-rich volcanogenic massive sulphide deposits (e.g. Morton and Franklin, 1987; Dubé et al., 2007a; Mercier-Langevin et al., 2007, 2011), although it would target mineralization with higher tonnage and high ratios of Au (ppm) to base metal (wt%).

Sericite-altered calc-alkalic dacite domes, flows, and flow breccia, bounded by tholeiitic mafic to intermediate volcanic rocks could define an exploration target for deposits similar to Rainy River. Another good indicator to mineralization at Rainy River, which could help further define future exploration targets, is the presence of alteration minerals such as Fe- to Mg-rich carbonate minerals, spessartine garnet, rutile, and aluminosilicate minerals, including chloritoid.

Though the Rainy River project can be considered as a large-tonnage and "low-grade"-style operation, it differs from many other "large-tonnage, low-grade"-style Au deposits recently discovered or put into production in the Superior Province, such as Côté Gold, Hammond Reef, Canadian Malartic, and Troilus, which implies that exploration strategies cannot be universally applied to such types of deposits. The ~10 Moz Hammond Reef deposit consists of a low-sulphide, syn-deformation quartz stockwork-type Au mineralization associated with shallowly dipping, anastomosed shear zones that crosscut the dominantly tonalitic Marmion batholith north of the Quetico fault, contrasting with the sulphide-associated Au at Rainy River. The ~7.6 Moz Au Côté Gold deposit is hosted in a calc-alkaline diorite-tonalite intrusive complex in the Swayze belt. The Coté Gold deposit is associated with a magmatic-hydrothermal breccia and Au±Cu mineralization that consists mainly of finely disseminated pyrite and chalcopyrite (±veins), this mineralization being considered syngenetic (Katz et al., 2014). This mineralization style contrasts with the volcanic host succession and the Au±Zn-Ag-Cu association at Rainy River. The ~10 Moz Au Canadian Malartic deposit consists of very finely disseminated auriferous pyrite and quartz-carbonate-pyrite veinlets and veins hosted in metagreywacke of the Pontiac Subprovince and late monzonitic porphyritic intrusions just south of the Cadillac-Larder Lake fault zone. The mineralization at Canadian Malartic is associated with potassic (biotite and potassium feldspar) and carbonate alteration zones and is considered as orogenic, with possible input from intrusions (de Souza et al., 2014, 2015), which again contrasts with the inferred early timing, volcanic setting, sericite-dominated alteration, and Au-base metal association at Rainy River. The ~2 Moz Au Troilus deposit in the Frotet-Evans belt is hosted in a calc-alkaline dioritic intrusion and is associated with a magmatic-hydrothermal pseudo-breccia that consists of early albitization crosscut by potassic alteration; the Au-Cu mineralization consists mainly of finely disseminated pyrite and chalcopyrite (±veins) and is interpreted as a reduced porphyry-style system (Rowins, 2011). This deposit is also in contrast to the volcanic setting and the Au±Zn-Ag-Cu association at Rainy River. The Mount Lyell mining district in Tasmania, hosted in the Cambrian Mount Read Volcanics, is a good example of a "large tonnage-low grade"-style Au deposit formed in the VMS environment. In this Cu-Au±Pb-Zn system, the bulk of the Cu-Au mineralization occurs as disseminated chalcopyrite-pyrite-bornite ore bodies associated with a >6 km-long pervasive sericite-chlorite-pyrite-silica alteration zone. Minor Pb-Zn-rich massive sulphide and limestone lenses characterize the exhalative zone above the Cu-rich orebodies and represent the upper part of an inferred hybrid magmatic-seawater system (Corbett et al., 2001). At Rainy River, the high Au/base metal ratio and the presence of both Cu and Zn mineralization within the main sericite-dominated alteration zone contrast with the Pb-Zn and Cu zonation at Mount Lyell.

FUTURE WORK

Current and future work will focus on analyzing the effects of structural deformation and hydrothermal activity on the distribution and grades of mineralization. In addition, sulphide chemistry, Cu and Zn isotopes, whole-rock oxygen isotope mapping, and U/Pb geochronology will help better define mineralization style and timing, providing key tools to improve genetic and exploration models for similar "atypical" Archean Au systems at various scales.

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