The metamorphosed Cambro-Ordovician Ming volcanogenic massive sulfide deposit in northern Newfoundland, Canada, is locally overlain by a unit consisting of mafic to intermediate medium- to coarse-grained volcanioclastic breccia with up to 10 vol % sulfide clasts. Analysis via mineral liberation analyzer of two sulfide clasts, completed using scanning electron microscope observations, allowed the identification of a number of microscopic and submicroscopic electrum grains. These electrum grains occur in three types of textural settings: (1) free electrum grains with tellurides within gangue minerals, (2) inclusions of electrum with tellurides in pyrrhotite grains, and (3) free electrum grains with base metals and tellurides interstitial between base metals and along cataclastic fractures in pyrite. These three textural settings are similar to those in the underlying massive sulfide orebodies that represent very likely sources to the sulfide clasts. The polyhedral nature and angularity of the volcanioclastic fragments in the breccia suggest a postmineralization gravity-controlled debris flow proximal to its source. The mineral assemblage and textures of electrum in the sulfide clasts implies evidence in support of syngenetic and predeformation Au introduction in the volcanogenic massive sulfide deposit, and argues against an orogenic overprint as the cause for Au enrichment.

The goals of this study are as follows: (1) the identification of Au-bearing minerals inside the sulfide clasts, (2) characterization of their textures and mineral associations, and (3) comparison with the previously studied underlying massive sulfide orebodies (Brueckner et al., 2014, 2016). These results are then utilized to provide insight into Au provenance within the clasts and to assess whether Au enrichment was syngentic or epigenetic.
**Geologic Setting**

The geology of the Ming deposit and its regional setting are well documented (Tuach and Kennedy, 1978; Hibbard, 1983; Castonguay et al., 2009; Skulski et al., 2010; Pilote and Piercey, 2013; Pilote et al., 2014, 2015), and only a brief summary will be presented here. The Ming deposit is hosted by Cambro-Ordovician (c. 487 Ma) intermediate to felsic rocks of the informally named Rambler Rhyolite formation, Baie Verte Peninsula, Newfoundland (Fig. 1; Hibbard, 1983; Skulski et al., 2010). The Rambler Rhyolite formation forms the upper part of the Cambro-Ordovician Pacquet Complex, which is a partial ophiolite sequence (Hibbard, 1983) of the Baie Verte oceanic tract (van Staal, 2007). The Pacquet Complex is defined at its base by low Ti boninites, locally cogenetic felsic tuffs, and rhyodacitic flows (Hibbard, 1983; Piercey et al., 1997), and pillowed intermediate Ti boninites (Skulski et al., 2010). The Pacquet Complex is unconformably overlain by a sequence of the Early to Middle Ordovician Snooks Arm Group that includes, starting at its base, magnetite-rich siltstone, tholeiitic mafic volcanic rocks, volcanioclastic and epiclastic fragmental rocks, and calc-alkaline flows and fragmental rocks (Skulski et al., 2010).

The Rambler Rhyolite formation is defined by a 6-km-wide and 2.5-km-thick folded dome-shaped sequence of quartzphyric rhyodacite, quartz-bearing intermediate to felsic tuff, and tuff breccia (Tuach and Kennedy, 1978; Hibbard, 1983; Skulski et al., 2010). The Ming deposit, located in the upper part of the Rambler Rhyolite formation, consists of five orebodies that are hosted within variously hydrothermally altered intermediate to felsic volcanic rocks with a large portion of volcanioclastic rocks. The five orebodies are from the northwest to the southeast: 1807 zone, 1806 zone, Ming North, Ming South and Lower Footwall zone (Fig. 2).

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**Fig. 1.** Simplified geologic map of the Pacquet Complex with the Ming VMS deposit (modified after Skulski et al., 2010). The different orebodies of the Ming deposit are projected to surface.
They consist of strata-bound semimassive to massive sulfides lenses and underlying discordant sulfide stringers. The orebodies are Cu rich, precious metal bearing, and locally enriched in Zn. The sulfide assemblage in the orebodies is complex and is dominated by a pyrite-chalcopyrite assemblage with minor pyrrhotite-sphalerite and traces of galena-arsenopyrite ± cubanite ± sulfosalts ± tellurides ± (sulfo-)antimonides ± precious metals ± oxides (Brueckner et al., 2014, 2016).

Three generations of mafic to intermediate intrusive rocks are present in the deposit. They each have distinctive litho-geochemical signatures and are interpreted to be genetically related to the mafic rocks of the Snooks Arm Group cover sequence (Pilote and Piercey, 2013; Pilote et al., 2014, 2015).

Alteration, deformation, and metamorphism

The Rambler Rhyolite formation, host to the Ming deposit, is overprinted by Cambro-Ordovician moderate to intense hydrothermal alteration (Pilote et al., 2014, 2015). Rocks overlying the massive sulfide orebodies of the Ming deposit postdate mineralization and, therefore, escaped ore-related hydrothermal alteration. Silurian-Devonian upper green-schist- to lower amphibolite-grade metamorphism affected all rocks of the Rambler Rhyolite formation and Snooks Arm Group (Gale, 1971; Tuach and Kennedy, 1978; Castonguay et al., 2009, 2014), including at least four phases of regional deformation (D1 to D4), with D2 (and M2) being the most intense (Tuach and Kennedy, 1978; Hibbard, 1983; Castonguay et al., 2009, 2014). Late syn- to post-D2 biotite, epidote, actinolite, carbonate, and sulfides porphyroblasts overprint structural fabrics defined by various assemblages predominantly composed of quartz-sericite-chlorite-epidote-sulfides, observed within and outside the deposit (Gale, 1971; Tuach and Kennedy, 1978).

Geology of diamond drill hole RMUG13-205

Sulfide clasts described in this study are found in diamond drill hole RMUG13-205, which was drilled in the up-plunge section of the 1807 zone as part of an underground definition drilling program (Fig. 2). The thickness for each unit reported here is core length and a stratigraphic column is shown in Figure 3. The hole intersects a 3.5-m-thick semimassive to massive sulfide horizon with significant Cu, Ag, and Au contents (11.7 wt % Cu, 17.6 g/t Ag, and 2.7 g/t Au over 0.45 m), and is a critical drill hole to test the source of Au in the clasts given the elevated Au grades.

Composition and texture of the sulfides within the (semi-) massive sulfide horizon vary from medium-grained equigranular pyrite to coarse-grained, subrounded pyrite supported by a chalcopyrite- and galena-bearing matrix (Fig. 4a). The sulfide horizon contains up to 10 vol % intermediate volcanic rock fragments that are quartz altered (Fig. 4b). The stratigraphy immediately below the (semi-)massive sulfide horizon is cut by a 6.5-m-thick dark green, chlorite-carbonate-altered, fine-grained gabbro separating the intermediate volcanic rocks from the sulfides. Two intervals of sulfide veins are enclosed within the gabbro with contacts at moderate angle to core axis. A similar mafic dike is repeated at depth. The two dikes enclose a 3.5-m-thick section of fine-grained, actinolite-chlorite-altered, intermediate coherent volcanic rock. Both dikes show chilled margins with the volcanic rock and sulfides.

The (semi-)massive sulfide horizon is immediately overlain by a 10-m-thick unit of polymictic breccia of mafic to intermediate composition. This unit contains clasts of different compositions including sulfide-bearing clasts and dark purple to medium gray quartz and quartz-sericite hydrothermally altered coherent rhyodacite clasts (Fig. 4c, d). The sulfide clasts locally make up to 10 vol % of the rock, whereas the rhyodacitic clasts make up to 30 vol %. The majority of the sulfide and silicate clasts are subrounded to subangular, vary in size (<5 cm), and stretched coaxial to the main stretching lineation related to D2. The matrix of the breccia is fine to medium grained, foliated, and is composed of an assemblage of recrystallized quartz-plagioclase-epidote-chlorite, with biotite grains forming postkinematic porphyroblasts, commonly
overprinting chlorite (Fig. 4e). The biotite porphyroblasts are related to younger Silurian-Devonian (or younger) regional metamorphism. Late quartz-epidote veins with traces of sulfide minerals cut the rock and are transposed into the dominant foliation (Fig. 5a). These postmineralization, but predeformation, veins are also found crosscutting the underlying massive sulfide orebodies, the felsic footwall rocks, and the mafic dikes and only locally contain traces of pyrite and chalcopyrite (Pilote and Piercey, 2013; Pilote et al., 2014). Gold- and Te-bearing minerals have yet to be found within these veins.

The volcaniclastic unit is overlain by a thin (≤1 m), dark purple to black, magnetite-rich siltstone (Fig. 4f). This sedimentary horizon represents the base of the Snooks Arm Group and can be traced throughout the deposit (Skulski et al., 2010; Pilote et al., 2015).

**Methodology and Sampling**

Sulfide clasts (samples 205-2 and 205-3) were extracted from the volcaniclastic unit in RMUG13-205 (Fig. 5a, b). The clast samples were collected from drill core, 8.4 and 9.0 m above the upper part of the (semi-)massive sulfide zone. A chip from sample 205-2 was cut parallel to the elongation of the clast, whereas 205-3 was cut perpendicular to the elongation. The chips were then mounted in 40-mm-diam resin rounds to obtain a maximum surface area for analysis, followed by polishing and the application of a carbon coating. The MLA measurements were made on an FEI MLA 650 field emission gun SEM instrument at the CREAT Centre, Memorial University. Operating conditions included an accelerating voltage of 15 kV and an imaging scan speed of 8 μsec. The use of 15 kV allows for a better resolution during analyses and for imaging on grains of small dimensions (≤5 μm). The mounds were measured in extended backscattered electron (XBSE) mode using a beam current of 10 nA and a spot size of 5.77. X-ray analyses were triggered for a BSE range of 125 to 235; each X-ray measurement was acquired for 10 msec on a 0.5- × 0.5-mm frame with a resolution of 1,000 dpi. Data reduction was performed on MLA Data View (FEI) software version 3.1.4.683.
Fig. 4. Representative and selected drill core photographs of diamond drill hole RMUG13-205. (A). Massive sulfide consisting of rounded, coarse-grained pyrite with interstitial chalcopyrite, galena, and sphalerite. (B). Massive sulfide consisting primarily of fine-grained pyrite-chalcopyrite ± sphalerite with quartz-altered aphanitic rhyodacite fragments. (C). Polymictic medium- to coarse-grained intermediate breccia with rhyodacite and sulfide clasts. Note the elongation of the clasts due to deformation. (D). Subangular quartz-altered rhyodacite in the fine-grained portion of the volcaniclastic unit. (E). Close-up of the fine-grained matrix of the breccia consisting of quartz-plagioclase-sericite-biotite ± epidote ± chlorite. Note the biotite porphyroblasts. (F). Magnetite-rich siltstone overlying with a sharp contact the volcaniclastic unit. Mineral abbreviations are as in Figure 3.

Fig. 5. Photographs of samples (A) 205-2 and (B) 205-3 selected for SEM-MLA analyses.
Sulfide Mineralogy and Mineral Textures of the Sulfide Clasts

Sulfide mineralogy

The clasts are composed of a pyrite > chalcopyrite > sphalerite > quartz ≈ biotite assemblage that makes up more than 99.9 wt % of the samples (Fig. 6). The remaining percentage consists of an assemblage of tellurides (coloradoite, hessite, and Bi telluride), sulfides (arsenopyrite, galena, and pyrrhotite), oxides (cassiterite and hematite), and precious metals (mercurian electrum). The wide range of trace mineral phases identified in both samples with MLA underlines the complex ore mineralogy in the sulfide clasts. Table 1 shows results of MLA with values normalized to the abundance of the aforementioned list of trace minerals to emphasize their relative abundances. Gold-bearing minerals were identified with MLA as minerals with >10 wt % Au. Brueckner et al. (2014, 2016) showed that Au occurs predominantly as (mercurian) electrum at the Ming deposit orebodies. Although the relative abundances of Ag, Au, and Hg in electrum vary (Brueckner et al., 2014, 2016), distinctions between the different Au-bearing alloys in the clasts are difficult to make using MLA due to the semiquantitative detection and the small size of the analyzed grains. Hence, the term electrum is used in this paper for all Au-bearing phases that have >10 wt % Au.

Precious metal textures

Textures of electrum in the sulfide clasts can be divided into: (1) free electrum with telluride grains within gangue minerals (Fig. 7a); (2) inclusions of electrum with telluride in pyrrhotite (Fig. 7b); and (3) free electrum grains with base metals and tellurides interstitial between base metals and along cataclastic fractures in pyrite (Fig. 7c, d).

The first texture is characterized by the contact of electrum with gangue phases (quartz, biotite, chlorite, epidote, albite, and white micas) where quartz is the predominant

Table 1. Result Data of Trace Minerals from MLA in Samples 205-2 and 205-31

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mineral</th>
<th>Formula</th>
<th>Wt %</th>
<th>Area (%)</th>
<th>Area (μm²)</th>
<th>Particle count</th>
<th>Grain count</th>
<th>Wt %</th>
<th>Area (%)</th>
<th>Area (μm²)</th>
<th>Particle count</th>
<th>Grain count</th>
</tr>
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<tr>
<td>RMUG13-205-2</td>
<td>Arsenopyrite FeAsS</td>
<td>0.29</td>
<td>0.29</td>
<td>63.00</td>
<td>23</td>
<td>23</td>
<td>9.29</td>
<td>10.13</td>
<td>1,532.00</td>
<td>60</td>
<td>60</td>
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<tr>
<td></td>
<td>Cassiterite SnO₂</td>
<td>0.15</td>
<td>0.13</td>
<td>28.25</td>
<td>4</td>
<td>4</td>
<td>0.18</td>
<td>0.17</td>
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<td>9</td>
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<tr>
<td></td>
<td>Coloradoite HgTe</td>
<td>0.93</td>
<td>0.71</td>
<td>154.00</td>
<td>12</td>
<td>12</td>
<td>0.89</td>
<td>0.73</td>
<td>110.50</td>
<td>9</td>
<td>9</td>
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<td></td>
<td>Electrum (Au,Ag)</td>
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<td>678.50</td>
<td>98</td>
<td>98</td>
<td>14.60</td>
<td>7.93</td>
<td>1,198.50</td>
<td>140</td>
<td>144</td>
<td></td>
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<tr>
<td></td>
<td>Galena PbS</td>
<td>3.13</td>
<td>2.53</td>
<td>552.50</td>
<td>185</td>
<td>185</td>
<td>6.41</td>
<td>5.61</td>
<td>847.75</td>
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<td></td>
<td>Hematite Fe₂O₃</td>
<td>0.63</td>
<td>0.73</td>
<td>159.50</td>
<td>25</td>
<td>25</td>
<td>0.02</td>
<td>0.03</td>
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<td></td>
<td>Hessite Ag₂Te</td>
<td>29.49</td>
<td>23.73</td>
<td>5,181.75</td>
<td>406</td>
<td>411</td>
<td>14.60</td>
<td>7.93</td>
<td>1,198.50</td>
<td>140</td>
<td>144</td>
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<td></td>
<td>Pyrrhotite Fe₁₋ₓS</td>
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<td>21.94</td>
<td>4,930.00</td>
<td>1,592</td>
<td>1,597</td>
<td>5.68</td>
<td>8.18</td>
<td>1,237.00</td>
<td>809</td>
<td>811</td>
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<td></td>
<td>Bi-telluride (Bi₂Te₃)</td>
<td>37.32</td>
<td>29.26</td>
<td>6,390.00</td>
<td>218</td>
<td>220</td>
<td>3.81</td>
<td>3.23</td>
<td>488.75</td>
<td>69</td>
<td>70</td>
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<tr>
<td></td>
<td>Unknown²</td>
<td>6.04</td>
<td>18.48</td>
<td>4,034.50</td>
<td>1,754</td>
<td>1,770</td>
<td>5.11</td>
<td>16.92</td>
<td>2,557.50</td>
<td>1,272</td>
<td>1,295</td>
<td></td>
</tr>
<tr>
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<td></td>
<td>100.00</td>
<td>100.00</td>
<td>21,835.00</td>
<td>4,317</td>
<td>4,345</td>
<td>100.00</td>
<td>100.00</td>
<td>15,119.00</td>
<td>3,270</td>
<td>3,312</td>
<td></td>
</tr>
</tbody>
</table>

1 The list excludes major minerals (pyrite, chalcopyrite, sphalerite, quartz, and biotite) present in the samples and values listed (area (%) and wt %) are normalized to 100% relative to the total area covered by the minerals (in μm²)
2 Minerals with unknown X-ray spectra
gangue mineral in contact with electrum (Fig. 7a). The silicified horizon capping and the stringer zone underlying the 1806 zone also show this type of precious metal texture (Fig. 8a, b; Brueckner et al., 2014, 2016). However, within the sulfide clasts, electrum is also in contact with epidote. Moreover, hessite and Bi telluride, and fine-grained chalcopyrite are proximal to electrum in the hosting gangue mineral assemblage of the clasts. The origin of this texture is unclear and is either attributed to syngenetic deposition or internal remobilization during Silurian-Devonian deformation and

Fig. 7. Backscattered electron images and energy dispersive X-ray (EDX) scans by SEM on samples 205-2 and 205-3 for selected elements. Semiquantitative EDX images show intensities (or relative abundance) of the measured elements. (A). BSE (left) image showing electrum occurring with Bi telluride (BiTe), hessite with gangue minerals such as chlorite, quartz, and epidote. EDX (right) scan of Ag and Au highlighting electrum (i.e., Au = lime green) and hessite (i.e., Ag = red). (B). BSE (left) image showing the occurrence of electrum, enclosed in pyrrhotite, with hessite in contact with chalcopyrite and pyrite. Hessite also occurs along a fracture in a recrystallized pyrite grain. Both chalcopyrite and pyrrhotite are enclosed in pyrite. EDX (right) scan of Ag and Au highlighting electrum (Au = green) and hessite (Ag = red). Note the light red color of electrum indicating a high Ag content. (C). Free grains of electrum coexisting with chalcopyrite and recrystallized pyrite. (D). Brittle fractures in pyrite filled with electrum and sphalerite in close spatial associations with chalcopyrite. Mineral abbreviations are as in Figure 3 with the addition of: hes = hessite.
metamorphism (Brueckner et al., 2016). Although uncommon, epidote is also found as a gangue mineral, together with quartz, muscovite, and carbonate minerals in the 1807 massive sulfide orebody (Fig. 8c, d).

In the second texture, electrum occurs with hessite in pyrrhotite (Fig. 7b). This texture is the most abundant precious metal texture in the observed sulfide clasts. Electrum marginal on chalcopyrite on contact to (silicic) gangue and adjacent to sphalerite and unknown AgCuFeS phase (silicified horizon in contact with massive sulfides, 1806 zone). (C). and (D); Gangue minerals in pyrite-sphalerite-chalcopyrite-rich massive sulfide under transmitted (cross-polarized) and reflected light, respectively (1807 zone). (E). Electrum as inclusions in and marginal to pyrrhotite, together with arsenopyrite and sphalerite (silicified horizon in contact with massive sulfides, 1806 zone). (F). Electrum with galena and spatially close sphalerite and Bi telluride (BiTe) between recrystallized pyrite (massive sulfides, Ming South zone). Mineral abbreviations: apy = arsenopyrite, cal = calcite, ccp = chalcopyrite, el = electrum, ep = epidote, gn = galena, gud = gudmundite, mia = miargyrite, mus = muscovite, po = pyrrhotite, py = pyrite, qtz = quartz, sp = sphalerite. Photomicrographs in (A), (B), and (F) are after Brueckner et al. (2016) and (E) from Brueckner et al. (2014).

Discussion

Volcaniclastie rocks locally overlying the Ming VMS deposit are enriched in Au and provide critical insight into the origin of Au enrichment in this deposit. Two main models have been invoked for Au enrichment in VMS deposits: syngenetic (e.g., Hannington et al., 2005) and epigenetic (e.g., Evans, 1999). In the clast-rich unit, mineral assemblages and ore textures involving electrum provide key information required to test the syngenetic versus epigenetic origin of Au enrichment.

First, the distribution of electrum and spatially closely associated minerals (e.g., tellurides) in the volcaniclastic unit are confined to the sulfide clasts. This is shown in sample 205-2 where an MLA scan was done beyond the extent of the sulfide clast, into the host breccia and a crosscutting quartz-carbonate vein (Fig. 6b). The input of precious metals from an external source such as an epigenetic style of Au enrichment (e.g., orogenic) would typically result in the deposition of Au within structurally controlled veins and/or fabrics, commonly discordant to and/or associated with carbonate alteration (Dubé and Gosselin, 2007). However, the clasts and their surrounding within the 10-m volcaniclastic unit show no evidence of such features. The presence of electrum exclusively within the clasts and the absence of an overprint of ore-forming fluidrelated alteration is, therefore, direct evidence for Au enrichment prior to the deposition of the volcaniclastic unit.

In Table 2, precious metal textures observed in sulfide clasts and (semi-)massive sulfides of the Ming deposit are compared. Although there are minor differences, the majority of textures and assemblages found in the clasts are remarkably similar to the (semi-)massive sulfide ores (Fig. 8). Furthermore, the hydrothermally altered volcaniclastic clasts exhibit similar alteration as the underlying footwall volcaniclastic host rocks, together with the sulfide clasts that are spatially restricted and proximal to massive sulfide mineralization, suggest a provenance from the immediately underlying host assemblage and mineralization, respectively. Collectively, the above results support a syngenetic, rather than an epigenetic, origin for precious metal-enrichment at the Ming deposit.

Au-Te association

The presence of tellurides in VMS deposits is generally uncommon, nevertheless, the presence of Te-bearing minerals in close textural association with Au-bearing minerals has been recorded in some metamorphosed VMS deposits (e.g., Abitibi, Egypt, Urals; see Appendix 1). Telluride coexistence with native gold/electrum, and the possible processes of transport and deposition, have also been documented in modern hydrothermal systems in volcanic arcs and back-arc basins (Watanabe and Kajiruma, 1994; Moss and Scott, 2001; Hannington et al., 2005), and some well-preserved ancient unmetamorphosed VMS deposits (Maslennikova et al., 2008; Maslennikov et al., 2009). Tellurium in VMS deposits is likely to be of magmatic origin as it is commonly mineralogically and chemically associated with other magmatophile volatiles (e.g., Bi, Tl, Sn, Se), and less likely from the hydrothermal
leaching of the host rocks (Patten et al., 2015). Tellurium is predominantly transported in the vapor phase (Affifi et al., 1988; Gründler et al., 2013), but the transport as minor aqueous species can also occur, but is rarer (Zhang and Spry, 1994; McPhail, 1995). Transport conditions of Te in VMS deposits occur in a wide range of temperatures (Maslennikov et al., 2009), and typically in reduced fluids with a high $f_{\text{O}_2}/f_{\text{S}_2}$ ratio (Affifi et al., 1988; Zhang and Spry, 1994). Decrease of the latter ratio, increase of the $f_{\text{O}_2}$, and/or decrease of temperature due to seawater mixing leads to the precipitation of telluride minerals and/or substitution of $S^{2-}$ by $Te^{2-}$ in other minerals (e.g., galena and arsenopyrite; Affifi et al., 1988; Zhang and Spry, 1994; Brueckner et al., 2016). Syngenetic coprecipitation of Au and Te is suggested in some metamorphosed and unmetamorphosed VMS deposits of the Urals, as illustrated by the elevated Au contents (up to 5.2 wt % Au) in telluride minerals (Vikentyev, 2006).

The intimate relationship between Au and Te at the Ming deposit is demonstrated by the close spatial association between electrum and tellurides such as hessite and Bi telluride. Much like electrum, the tellurides are restricted to the sulfide clasts and the underlying (semi-)massive sulfide orebodies (Brueckner et al., 2014, 2016). Moreover, orogenic Au deposits hosted in the Snooks Arm Group that occur 10 to 20 km north of the Ming deposit have distinct ore mineralogy and associated minerals (Vikentyev, 2006).

The application of MLA allowed answering the fundamental questions outlined in this study in a relatively short analytical time frame (~20 h) and significantly minimized the potential for operator bias and human error (e.g., overlooking the proximal deposition rather than distal. The presence of associated altered volcaniclastics (mostly silicified; Fig. 4d) in this unit is also an indication of the proximity of the source. Moreover, owing to textural resemblance of the electrum grains and associated minerals with textures observed in the underlying orebodies, it is extremely likely that the sulfides originated from the 1806 and/or 1807 zones of the deposit; hence, the sulfide-rich breccia is restricted to the 1806 and 1807 zones of the deposit (Pilote et al., 2007b, Mercier-Langevin et al., 2007), and one could argue that with permissive dynamic properties of the host mass flow, small-size fragments, including the sulfide clasts, can travel substantial distances (i.e., kilometers; McPhie et al., 1993). However, the sulfide-rich breccia is restricted to the 1806 and 1807 zones of the deposit; hence, gravity-controlled debris flow rather than a pyroclastic flow (Fig. 9; McPhie et al., 1993). It is difficult to determine the specific cause of this flow but considering (1) the formation of nearby intermediate to rhyolitic dome(s) and synchronous mafic volcanic rocks based on the current understanding of the regional geologic setting (Cas tonguay et al., 2009; Skulski et al., 2010), (2) volcanic architectural reconstruction of the deposit (Pilote et al., 2015), and (3) the chaotic paleo-seafloor topography in this type of environment (Ross and Mercier-Langevin, 2014), collapse of at least part of the marginal domal edifice may have triggered mass flow of volcanic debris. During this process, the sulfide clasts were derived from the underlying (semi-)massive sulfides along its flow path and incorporated into the volcaniclastic unit (Fig. 9). The sulfide clasts are relatively small (≤5 cm across) compared to sulfide-rich debris flows overlying other VMS deposits (e.g., Bousquet-Laronde; Dubé et al., 2007b, Mercier-Langevin et al., 2007), and one could argue that with permissive dynamic properties of the host mass flow, small-size fragments, including the sulfide clasts, can travel substantial distances (i.e., kilometers; McPhie et al., 1993). However, the sulfide-rich breccia is restricted to the 1806 and 1807 zones of the deposit; hence, the sulfide-rich breccia is restricted to the 1806 and 1807 zones of the deposit (Pilote et al., 2014, 2015). In particular, the syndeformation quartz-carbonate veins hosting native Au in the orogenic Au deposits are devoid of tellurides (Copeland et al., 2015), and formed at higher temperatures (480°C ≥ T >250°C; Ramezani et al., 2000) than the hydrothermal fluids that precipitated electrum (T = 260°-300°C) and tellurides (<260°C) in the Ming deposit (Brueckner et al., 2016). Although the Ming deposit was affected by extensive deformation and upper greenschist-lower amphibolite metamorphism, the tellurides and electrum reside in the orebodies and sulfide clasts are spatially associated with one another, and exhibit no evidence of postmineralization enrichment (Brueckner et al., 2016). Therefore, a syngenetic Au-Te enrichment of the Ming VMS deposit is proposed.

**Genetic implications**

The poly lithic nature and angularity of the volcaniclastic fragments in the breccia are suggestive of a postmineralization gravity-controlled debris flow rather than a pyroclastic flow. The intimate relationship between Au and Te at the Ming deposit is demonstrated by the close spatial association between electrum and tellurides such as hessite and Bi telluride. Much like electrum, the tellurides are restricted to the sulfide clasts and the underlying (semi-)massive sulfide orebodies (Brueckner et al., 2014, 2016). Moreover, orogenic Au deposits hosted in the Snooks Arm Group that occur 10 to 20 km north of the Ming deposit have distinct ore mineralogy and associated minerals (Vikentyev, 2006).
presence or underestimating the amount of microscale precious metal grains due to grain size), and at a much higher resolution compared to common petrographic or exploratory SEM methods (Sylvestre, 2012). Although, the application of MLA is often focused in applied mineralogy and metallurgical processes (Fandrich et al., 2007; Ford et al., 2011; Kelvin et al., 2011), heavy mineral provenance in sediments and sedimentary rocks (Lowe et al., 2011; Tsikouras et al., 2011), and till and stream-sediment prospecting (Wilton and Winter, 2012), it can be a strategic tool when used with basic geologic, stratigraphic, mineralogical, and alteration observations to solve genetic problems in the study of metallic mineral deposits.

**Conclusions**

The use of SEM-MLA on natural samples has shown to be an effective analytical method in detecting a range of submicroscopic minerals, such as electrum. Hence, we were able to identify all the electrum grains (≥0.5 μm in size) present on cut surfaces of sulfide-bearing clasts that are part of a volcaniclastic unit, immediately overlying the Cambro-Ordovician Ming VMS deposit. The SEM-MLA results show that electrum is restricted to the sulfide clasts and share similar textural characteristics and mineral associations with the underlying 1806 and 1807 massive sulfide orebodies. The presence of electrum in the sulfide clasts with textural and assemblage features identical to underlying massive sulfide mineralization is evidence for syngenetic and pre-deformation Au enrichment in the VMS deposit. The results herein also illustrate how SEM-MLA can be a useful tool to provide information to answer genetic questions on how mineral deposits form.

**Acknowledgments**

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## APPENDIX 1

Compilation of Known Telluride Occurrences in VMS Deposits Worldwide

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Main commodities</th>
<th>Geologic age</th>
<th>Geologic setting</th>
<th>Metamorphic grade</th>
<th>Telluride mineralogy</th>
<th>Telluride mineral association/assemblage</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gayskoe deposit</td>
<td>Cu(\geq)Zn (Au, Ag)</td>
<td>Middle</td>
<td>Ural Mts., Russia</td>
<td>Unknown</td>
<td>Hessite (Ag,Te), altaite (Pb,Te), calaverite (Bi,Te)</td>
<td>Tellurides associated with massive pyrite-chalcopyrite sulfides on flanks of deposit containing gold and sulfosalts but no tellurides other than Ag-sulfotellurides</td>
<td>Novoselov et al. (2006) and references therein</td>
</tr>
<tr>
<td>Tash-Tau deposit</td>
<td>Cu-Zn-Pb-Au±barite</td>
<td>Middle</td>
<td>Ural Mts., Russia</td>
<td>Unknown</td>
<td>Hessite (Ag,Te), cervelleite-like mineral</td>
<td>Tellurides occurring in bornite-bearing ore as trace mineral phases together with gold, electrum, jalpaite, germanite, and stromeyerite. Cervelleite-like mineral is associated with gold</td>
<td>Novoselov et al. (2006) and references therein</td>
</tr>
<tr>
<td>Degtyarsk deposit</td>
<td>Cu(\geq)Zn (Au, Ag)</td>
<td>Lower-Middle</td>
<td>Ural Mts., Russia</td>
<td>Unknown, but extensively deformed</td>
<td>Alkaita (PbTe), coloradoite (HgLTe), tellurium (Te)</td>
<td>Tellurides are routinely found in Cu- (but not when bornite is present) and Cu-Zn ores, and are associated with chalcopyrite-tennantite-tetraborite-galena</td>
<td>Vikentyev (2006) and references therein</td>
</tr>
<tr>
<td>Gaisk deposit</td>
<td>Cu(\geq)Zn (Au, Ag)</td>
<td>Lower-Middle</td>
<td>Ural Mts., Russia</td>
<td>Unknown, but extensively deformed</td>
<td>Tellurium (Te), tetraborite (Bi, Pb, Te), stuetzite (Ag, Te)</td>
<td>Discrete Cu-, Ag- and Te-tellurides contain solid-solution gold within pyrite, chalcopyrite, and sphalerite. Many tellurides contain solid-solution gold</td>
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</tr>
<tr>
<td>Safyanovsk deposit</td>
<td>Cu(\geq)Zn (Au, Ag)</td>
<td>Lower-Middle</td>
<td>Ural Mts., Russia</td>
<td>Unknown, but non-deformed</td>
<td>Calaverite (Ag,Te), muthmannite (Ag,AgTe2), pyrrhotite (Ag,AgTe2),</td>
<td>Discrete Cu-, Ag- and Te-tellurides contain solid-solution gold within pyrite, chalcopyrite, and sphalerite. Many tellurides contain solid-solution gold</td>
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<tr>
<td>Uchaly deposit</td>
<td>Zn-Cu (Au, Ag)</td>
<td>Lower-Middle</td>
<td>Ural Mts., Russia</td>
<td>Unknown, but extensively deformed</td>
<td>Tellurium (Te), tetraborite (Bi, Pb, Te), stuetzite (Ag, Te)</td>
<td>Discrete Cu-, Ag- and Te-tellurides contain solid-solution gold within pyrite, chalcopyrite, and sphalerite. Many tellurides contain solid-solution gold</td>
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<tr>
<td>Uzelginsk deposit</td>
<td>Zn-Cu (Au, Ag)</td>
<td>Lower-Middle</td>
<td>Ural Mts., Russia</td>
<td>Unknown</td>
<td>Tellurium (Te), tetraborite (Bi, Pb, Te), stuetzite (Ag, Te)</td>
<td>Discrete Cu-, Ag- and Te-tellurides contain solid-solution gold within pyrite, chalcopyrite, and sphalerite. Many tellurides contain solid-solution gold</td>
<td></td>
</tr>
<tr>
<td>Yaman-Kasy deposit</td>
<td>Cu(\geq)Zn (Au, Ag)</td>
<td>Silurian</td>
<td>Ural Mts., Russia</td>
<td>Absent, locally zeolite facies</td>
<td>Bi-Pb tellurides, altaite (Pb,Te), hessite (Ag,Te), stuetzite (Ag,Te), sylvanite (Ag,Te), tellurium (Te), tellurium oxides, Pb-Ag-Au tellurides</td>
<td>Disseminated tellurides in drusy chalcopyrite within sylvanite-chalcopyrite-pyrite-marcasite chimneys</td>
<td>Novoselov et al. (2006) and references therein Maaslenkov et al. (2009) and references therein</td>
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<tr>
<td>Deposit</td>
<td>Main commodities</td>
<td>Geologic age</td>
<td>Geologic setting</td>
<td>Metamorphic grade</td>
<td>Telluride mineralogy association/assemblage</td>
<td>Study</td>
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<tr>
<td>Babaryk deposit</td>
<td>Cu-Zn-Pb-Au±barite</td>
<td>Paleozoic</td>
<td>Ural Mts., Russia</td>
<td>Unknown</td>
<td>Cervelleite-like sulfotelluride</td>
<td>Novoselov et al. (2006)</td>
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<td>Sulfotelluride is in banded pyrite-chalcocpyrite-sphalerite-bornite-galena ores with tellanite-tetrahedrite as anhedral to elongated grains within galena. At the galena-borinite grain boundary. Associated minerals are chalcoite, stromeyerite and electrum.</td>
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<tr>
<td>Severo-Uvanyazhskoe deposit</td>
<td>Cu-Zn-Pb-Au±barite</td>
<td>Paleozoic</td>
<td>Ural Mts., Russia</td>
<td>Unknown</td>
<td>Hessite (Ag₂Te), cervelleite (Ag₄TeS)</td>
<td>Novoselov et al. (2006) and references therein</td>
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<td>Tellurides occur in polymetallic ore dominated by sphalerite-galena-tellanite-tetrahedrite with traces of electrum-native silver-argentite. Cervelleite is associated with electrum, native silver and acanthite.</td>
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<tr>
<td>Ming deposit</td>
<td>Cu(-Au)</td>
<td>Cambro-Ordovician</td>
<td>Appalachian Mts., Newfoundland, Canada</td>
<td>Upper greenschist/ lower amphibolite facies</td>
<td>Hessite (Ag₂Te), altaite (Pb₁Bi₂Te), unnamed Bi-telluride (Bi₃Te₂)</td>
<td>Brueckner et al. (2016) and this study</td>
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<td>Tellurides preferentially with galena ± sphalerite ± pyrrhotite within (semi-)massive sulfides. Tellurides never in direct contact with electrum.</td>
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</tr>
<tr>
<td>Um Samiuki deposit</td>
<td>Zn-Cu-Pb-Ag</td>
<td>Precambrian</td>
<td>Eastern Desert, Egypt</td>
<td>Greenschist facies</td>
<td>Cervelleite (Ag₂TeS), hessite (Ag₂Te)</td>
<td>Helmy (1999)</td>
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<td>Tellurides are associated with sphalerite-pyrite-chalcocpyrite-galena-borinite-tellanite-tetrahedrite-electrum. Cervelleite occurs as small, subhedral grains close to margins of hessite and galena or as inclusions in sphalerite, where it is associated with silver-rich borinite-chalcocpyrite-hessite.</td>
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<tr>
<td>Mattagami Lake deposit</td>
<td>Zn-Cu</td>
<td>Archean</td>
<td>Superior Province, Quebec, Canada</td>
<td>Greenschist facies</td>
<td>Altaite (Pb₁Bi₂Te), hessite (Ag₂Te), tsumoite (Bi₁Te), unnamed Bi-telluride (Bi₃Te₂), unknown Ag₆S₇ telluride (Ag₆S₇Te₂)</td>
<td>Thorpe and Harris (1973)</td>
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<td>Tellurides occurring in specific &quot;telluride zone&quot; partly within massive sulfide ore and partly within chloritized porphyritic metahyotite. Tellurides occurring with sphalerite-chalcocpyrite-cobaltite-pyrrhotite-pyrite</td>
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REFERENCES


