The Hemlo Gold Deposit, Ontario: An Example of Melting and Mobilization of a Precious Metal–Sulfosalt Assemblage during Amphibolite Facies Metamorphism and Deformation

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Abstract

The timing of mineralization at the Hemlo gold deposit has long been a controversial issue. We present arguments that use partial melting of the ore assemblage to explain the mechanism of ore mobilization and resolve problems with the model of premetamorphic mineralization. The results have implications for mine exploitation and exploration strategies. We show that the ore mineral assemblage underwent partial melting during middle-amphibolite facies metamorphism (600°–650°C, 6–7 kbars), primarily through breakdown of stibnite and arsenopyrite in a high-fS2 environment. Concurrent deformation led to segregation of the resulting Sb- and As-rich sulfosalt melt. Interaction between this melt and a range of unmelted sulfides led to further melting and incorporation of other elements into the melt. The gold-bearing melt was mobilized from compressional high-strain sites into dilational domains such as boudin necks and extensional fractures developed in competent lithologies. Ore minerals that did not melt significantly (pyrite, molybdenite, pyrrhotite, and sphalerite) were not extensively mobilized and largely remained within high-strain compressional domains. This segregation of melt from residue thus resulted in the observed heterogeneous distribution of ore minerals within the deposit. Crystallization of the sulfosalt melt produced a diverse suite of ore minerals, dominated by stibnite and realgar and containing an array of rare sulfosalts, native elements, intermetallic compounds, and tellurides. Some sulfosalt melt persisted to low temperature (<300°C), allowing continued small-scale, localized mobilization during late deformation. Although gold occurs at moderate concentrations within the compressional high-strain domains, it is particularly concentrated in the dilational domains, a consequence of its mobilization within a sulfosalt melt. Our model of partial melting of the ore mineral assemblage with consequent mobilization explains how ore minerals that are unstable even at greenschist facies conditions came to be hosted in structures that formed at or near the peak of amphibolite facies metamorphism.

Introduction

Melting of sulfide mineral assemblages during metamorphism of a preexisting mineral deposit has been recognized at a small number of localities (e.g., Hofmann, 1994; Mavrogenes et al., 2001; Tomkins and Mavrogenes, 2002). However, it is likely that sulfide melting has gone unrecognized at many other previously described mineral deposits (Frost et al., 2002). This is likely due to the difficulty in recognizing textures that can be unequivocally related to sulfide melt and a general lack of awareness that ore mineral assemblages can melt during metamorphism.

Recognition of sulfide melting is important because there are several implications for mine exploitation, as well as local and possibly regional exploration. For example, sulfide melts are highly mobile, with viscosities close to that of water (e.g., Dobson et al., 2000), and thus migrate easily (Tomkins and Mavrogenes, 2002), enabling melt accumulation in structurally favorable sites. These sites could potentially be located significant distances (possibly kilometers) away from where the melts were originally generated. In addition, sulfide melts strongly partition precious metals such as gold and silver (Mavrogenes et al., 2001; Frost et al., 2002; Tomkins and Mavrogenes, 2002), thus potentially leading to the formation of precious-metal–rich segregations and, perhaps, precious-metal halos or caps around the main sulfide orebody.

In this study, we examine the Hemlo gold deposit, which Frost et al. (2002), in a global review of sulfide melting during metamorphism, considered likely to have experienced sulfide melting during middle to upper amphibolite facies metamorphism. Hemlo, in central Ontario, Canada (Fig. 1), is currently Canada’s third-largest lode gold deposit (95 Mt at 8.0 g/t; Schnieders et al., 2000). Much of the research on Hemlo has focused on the timing of mineralization, relative to amphibolite facies metamorphism. Most early studies favored a postpeak metamorphic timing (Hugon, 1986; Masliwec et al., 1986; Walford et al., 1986; Hattori, 1987; Corfu and Muir, 1989; Johnston and Smyk, 1992; Pan and Fleet, 1992), although others supported a pre- or synmetamorphic timing (Cameron and Hattori, 1955; Goldie, 1985; Kuhns, 1986, 1988; Valliant and Bradbrook, 1986; Thode et al., 1991). In the mid-1990s, Kuhns et al. (1994), Gustafson (1995), and Michibayashi (1995) supported a premetamorphic timing.

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and Fleet and Pan (1995) and Pan and Fleet (1995) supported a postmetamorphic timing. Since then, all authors have favored a pre- to synpeak metamorphic timing for the mineralization (Johnston, 1996; Powell and Pattison, 1997; Powell et al., 1999; Bodycomb et al., 2000; Lin, 2001; Muir, 2002, Davis and Lin, 2003, Muir, 2003).

One of the main problems for a pre- or synpeak metamorphic timing is the occurrence of low- to moderate-temperature sulfide minerals (minerals stable only below 350°C–600°C) in middle amphibolite-grade host rocks. Several authors have noted that many of the ore minerals are not stable at these conditions, and consequently concluded that crystallization of these minerals must have postdated peak metamorphism (e.g., Burk et al., 1986; Harris, 1989). Powell and Pattison (1997) suggested that these minerals exsolved from a complex solid solution at peak metamorphic conditions. However, these authors did not consider the melting temperatures of the solid solutions and, more importantly, the melting relations between coexisting sulfide phases. Another enigmatic aspect of the Hemlo deposit is the heterogeneous...
distribution of ore minerals in relation to meso- and microstructural domains. Although much of the sulfide material in the deposit is situated in highly strained rocks, a significant volume of low- to moderate-temperature sulfosalts, as well as gold, is hosted in ductile structures formed at high temperature (e.g., Bodycomb et al., 2000). These structural features formed approximately concurrently with peak metamorphism and continued to be reactivated during postmetamorphic ductile deformation (Lin, 2001).

The primary aim of this paper is to examine the hypothesis that the ore mineral assemblage underwent partial melting during concurrent metamorphism and deformation, leading to mobilization of the melt. We first describe the ore assemblages and their distribution with respect to various meso- and microstructural domains within the deposit, and briefly discuss possible mobilization mechanisms. We then review experimentally determined phase relations between the relevant minerals, which show that melting was inevitable and that melting of some phases and lack of melting of others can explain the observed heterogeneity in ore mineral distribution within the deposit. The significance of our results to mine exploitation and exploration strategies is also discussed.

Geology of the Hemlo Gold Deposit

The general geology of the Hemlo gold deposit has been described in numerous papers (see Muir, 2002, for a detailed review). Only details relevant to this paper are included here. Hemlo is an Archean gold deposit, situated in the Hemlo-Schreiber greenstone belt of the Superior province (Wawa subprovince), northwestern Ontario. Williams et al. (1991) presented an overview of the regional geology of the Wawa subprovince, including the Hemlo-Schreiber greenstone belt. Hemlo is located within a zone of strong deformation, known locally as the Hemlo shear zone, which parallels the regional west-northwest structural trend.

The deposit is situated within a broad zone of metamorphosed alteration that is up to 400-m wide and more than 4-km long. The mineralization is divided into two segments known as the Main and West segments (Muir, 2002). Although both segments dip ~60° to the north, the Main Segment strikes at ~290° and the West Segment strikes at ~270° (Fig. 1). Both segments consist of zones of tabular, shear-zone–parallel mineralization. The Main Segment contains an upper Main Mineralized zone and a smaller, subparallel Lower Mineralized zone (Fig. 2), and the West Segment comprises a series of narrow, erratically mineralized, low-grade zones.

A range of rock types hosts mineralization, including metasedimentary rocks, quartz feldspar porphyry, barite metasediments, and a mafic fragmental unit (possibly volcaniclastic; Bodycomb et al., 2000). Barite is a major constituent of the deposit (Harris, 1989). These lithologies are affected by pervasive, prepeak metamorphic alteration that varies across the deposit, locally overprinted by (syn- to postpeak metamorphic?) fracture- and/or cleavage-controlled alteration (Muir, 2002). The premetamorphic alteration is thought to represent primary alteration associated with the original mineralization event (A.E. Williams-Jones, unpub. report for the Canadian Mineral Industry Research Organization, 1998). In general, pervasive alteration is narrower in the Main Segment than in the West Segment, a pattern followed by mineralization, which is also narrower and of a higher grade in the east. Pervasive alteration is characterized by enrichment in K, Au, Mo, Sb, As, Hg, Ba, and V, and depletion in Na, Ca, Mg, and Mn (Kuhns, 1986); although some parts, particularly in the West Segment, are characterized by enrichment in Na or Si and depletion in K (Muir, 1997). Mineralogically, the pervasive alteration is characterized by a central zone of K-feldspar-quartz-(muscovite-biotite) rocks surrounded by muscovite-quartz schists (A.E. Williams-Jones, unpub. report for the Canadian Mineral Industry Research Organization, 1998). Silicification, biotitization, and pyritization are thought to be important components of the potassic alteration. Mafic fragmental rocks in the ore zone typically display extensive biotitic alteration, which is locally overprinted by muscovitic alteration. Muir (2002) notes four types of fracture-controlled alteration, which include, in order of abundance, the following: feldspar, biotite, pyrite + feldspar, and carbonate. These occur independently of mineralization, although pyrite + felspar alteration typically involves enrichment in Au, Ba, Hg, and Mo within mineralized zones.

Five periods of deformation are thought to have affected the host rocks at the Hemlo deposit (Lin, 2001; Muir, 2002). D1 is recorded by locally preserved isoclinal folds, sheath folds, and fault zones (Muir, 2002), although it may be related to a single period of deformation that progressed into D2 (Lin, 2001; Muir, 2002). D2 was the dominant deformation event at Hemlo and is associated with development of the Hemlo shear zone, as well as tight to isoclinal folding. Ductile
deformation during D2 induced a degree of structural heterogeneity within the deposit, which is preserved as a series of micro- to mesoscale (100-μm to 1.5-m) dilatational domains within moderately to highly strained rock. These low-strain, dilatant domains are a consequence of competency contrasts that developed between relatively incompetent mica-rich rocks and relatively competent mica-poor rocks. The competent layers and veins were boudinaged and experienced extensive fracturing, producing dilational areas at the boudin necks and fractures. Fold hinges and pressure shadows behind isolated knots of competent material are other examples of dilational domains that formed in and around more competent units. These features are best preserved in quartz veins, many of which were so strongly folded and boudinaged by this event that they were dismembered into isolated quartz knots. In a period of northwest-directed transpression (Muir, 2003), D3 produced open to tight, z-shaped folds (indicating dextral shear), many of which are spatially associated with previously boudinaged feldspar porphyry dikes (Lin, 2001). The D3 dilational features were locally enhanced during D2. D2, D3 and D4 were minor, late events that produced kink bands and brittle faults, respectively.

The host rocks are interpreted to have experienced a single cycle of metamorphism, which peaked at 600° to 650°C and 6 to 7 kbars, and followed a clockwise P-T path (Powell et al., 1999). Based on the relationships of kyanite and sillimanite to fabrics and microstructures (Powell et al., 1999), peak metamorphism is interpreted to have reached during D2, with isothermal decompression commencing in the waning stages of D2. The continued production of ductile structures during D4 indicates that high temperatures prevailed during this event. The most recent interpretations of the timing of mineralization with respect to deformation indicate that ore emplacement occurred prior to or during the initial stages of D3 (Lin, 2001; Davis and Lin, 2003), or possibly during middle D3 (Muir, 2002; Muir, 2003). Davis and Lin (2003) have bracketed the age of mineralization between 2685 ± 4 Ma and 2677 ± 1 Ma.

Description and Distribution of the Ore Assemblages

More than 50 ore minerals at Hemlo fit into four general categories (Harris, 1989; Table 1): (1) common sulfides and sulfosalts, (2) Tl-Pb-Cu-Hg-Ag-bearing sulfosalts, (3) native metals and intermetallic compounds, and (4) tellurides and selenides. In this paper, we refer to stibnite (Sb2S3), realgar and orpiment (AsS3) as sulfosalts (strictly, a sulfosalt is a mineral with metal(s), metaloid(s), and sulfur), because As and Sb are metaloids, and this chemical distinction allows us to differentiate between sulfosalts and metallic sulfides, which melt at generally higher temperatures. The ore minerals are heterogeneously distributed with respect to meso- and microstructural domains throughout the deposit (Table 1). We have divided the ore mineral suite into two groups, based on structural association. Group I minerals are typically disseminated within higher strain, mica- and K-feldspar–rich domains, and include pyrite, molybdenite, pyrrhotite, sphalerite, and cinnabar. This group makes up the majority of sulfide material in the deposit, with pyrite and molybdenite accounting for >95 percent of the total sulfide volume. Group II minerals are volumetrically dominated by stibnite and realgar and comprise an array of rare sulfosalts, tellurides, and native minerals, including gold. These are preferentially concentrated in low-strain, structurally dilatant domains, and many rarely, if ever, occur in high-strain domains. Group I minerals also occur in low-strain, dilatant domains, although they are typically not more concentrated there than elsewhere. However, we have observed rare instances where sphalerite and/or pyrrhotite are concentrated in dilational domains. Some minerals, including gold, are commonly observed in both structural domain types and thus have been included in both groups. Others (e.g., Bodycomb et al., 2000) have similarly noted a heterogeneous ore mineral distribution. Group I minerals compose roughly 5 to 20 percent of the bulk rock volume (locally exceeding 50%), whereas Group II minerals make up <2 percent. Figure 3 illustrates schematically the distribution of Group I relative to Group II minerals at Hemlo.

Mineralization in higher strain compressional domains

Figure 4A and B shows examples of mineralization in high-strain compressional domains. The most common of these is banded pyrite, which consists of pyrite and silicate minerals, although minor pyrrhotite is present at some localities. Pyrite + molybdenite mineralization is also widespread within high-strain compressional domains. In many samples, the highly ductile nature of molybdenite has focused deformation such that the most molybdenite rich regions are typically the most highly strained. Sphalerite and cinnabar also occur in high-strain compressional regions. Harris (1989) noted that minor chalcopyrite and galena occur in some sphalerite-pyrite–bearing samples.

Figure 4C shows a typical example of K-feldspar–rich rock with abundant disseminated pyrite and minor molybdenite,
which is widespread at Hemlo (contrast has been adjusted to highlight Ba zoning in the K-feldspar). The granoblastic nature of this rock indicates lower strain than in the examples shown in Figure 4A and B. If layers such as this are part of a relatively undeformed thick sequence with little ductile material (mica and molybdenite), they are still considered compressional when compared with actively dilational structures. However, if two mica-rich layers occur on either side, this layer would typically be boudinaged, with dilational domains developed at the boudin necks.

Mineralization in dilational domains

Figure 5 shows the relationship between mineralization in compressional and dilational domains within the Main Ore zone. Although a wide range of ore minerals is situated in structurally dilatant sites, stibnite and realgar make up the bulk of the sulfide volume. At the mesoscopic scale, Group II minerals are concentrated at boudin necks in deformed, competent lithologies (Figs. 5 and 6A). At the microscopic scale, they (particularly realgar) are also distributed along a myriad of interconnected fractures within the competent unit (Figs. 5 and 6B). It is common for a large clot of stibnite and/or realgar to contain an array of rare Group II minerals along the periphery of the clot (Fig. 6C), a feature that is mirrored by smaller clots of other Group II minerals (Fig. 7). These large clots of stibnite ± realgar are typically central to an array of fractures (Fig. 6B) that are partially filled with less-common Group II minerals. Fractures are typically the sites that contain gold and the other native metals and intermetallic compounds (Fig. 6D), although they also occur along grain boundaries between coarse stibnite and realgar (Fig. 5). Many large clots of stibnite contain exsolution lamellae, usually of realgar, but also of some of the rare sulfosalts (Fig. 6E). Most stibnite analyses show that some As substitution for Sb is preserved (Table 1), and thus that the exsolution process is incomplete. Powell and Pattison (1997) also showed examples of rare minerals associated with stibnite and realgar.

Gold mineralogy and distribution

Gold (containing up to 26.9% Hg and 29.1% Ag) occurs in both compressional and dilational domains. The molybdenite-pyrite mineralization typical of higher strain compressional domains makes up the bulk of ore-grade material at Hemlo. However, in this study, gold has been found to be highly concentrated in the low-strain, dilational domains (Fig. 5), even when compared to extremely molybdenite rich samples. A typical bulk ore grade at Hemlo is on the order of 10 ppm Au (avg grade for the deposit is 9.9 ppm Au; Johnston, 1996), but we have observed several examples of dilational domains that contain well in excess of 100 ppm Au. In compressional regions, gold is typically sparse and very fine grained (<20 µm), whereas gold in dilational domains is both more abundant and coarser grained (up to 1 mm). Gold grains in dilational sites are commonly rimmed by native arsenic (Fig. 7A) and/or aurostibite (AuSb2; Fig. 7B, C), and have grain boundary contacts with many of the Group II minerals (examples are shown in Figs. 5 and 6). Hg and Ag are uniformly distributed in some gold grains and zoned in others, the zonation showing a relationship with adjacent
## TABLE 1. Ore Minerals Identified in the Hemlo Deposit: Their Compositions and Structural Associations

<table>
<thead>
<tr>
<th>Mineral Details</th>
<th>Hemlo details</th>
<th>Mineral Formula</th>
<th>Common sulfides and sulfosalts</th>
<th>Mineral Group</th>
<th>Abundance</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tetrahedrite</td>
<td>High-strain zones</td>
<td>Fe₂(S₂O₃)₂⁺</td>
<td>Very common</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sphalerite</td>
<td>0–29.5% Hg; 0–1.9% Fe; 0–6% Mn</td>
<td>ZnS</td>
<td>Common</td>
<td>Harris (1989), this study</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galena</td>
<td>High-strain zones</td>
<td>PbS</td>
<td>Uncommon</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Realgar</td>
<td>Low-strain, dilational zones</td>
<td>Fe₂S₃</td>
<td>Common</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arsenopyrite</td>
<td>Low-strain, dilational zones</td>
<td>As₂S₃</td>
<td>Uncommon</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>High-strain zones</td>
<td>CuFeS₂</td>
<td>Uncommon</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>High-strain zones</td>
<td>Fe₁₋ₓS</td>
<td>Variable</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arsenopyrite</td>
<td>High-strain zones</td>
<td>FeAsS</td>
<td>Variable</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chalcostibite</td>
<td>Low-strain, dilational zones</td>
<td>CuSbS₂</td>
<td>Rare</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baumhauerite</td>
<td>Low-strain, dilational zones</td>
<td>Pb₃As₄S₉</td>
<td>Rare</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criddleite</td>
<td>Low-strain, dilational zones</td>
<td>TlAg₂Au₃Sb₁₀S₁₀</td>
<td>Rare</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hutchisonite</td>
<td>Low-strain, dilational zones</td>
<td>Pb₄FeSb₆S₁₄</td>
<td>Rare</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tvalchrelidzeite</td>
<td>Low-strain, dilational zones</td>
<td>Hg₁₂(Sb₄.₇As₃.₃)S₁₅</td>
<td>Rare</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ullmanite</td>
<td>Low-strain, dilational zones</td>
<td>NiSbS</td>
<td>Rare</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paakkonenite</td>
<td>Low-strain, dilational zones</td>
<td>Sb₂AsS₂</td>
<td>Rare</td>
<td>Pan and Fleet (1992)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vaughanite</td>
<td>Low-strain, dilational zones</td>
<td>TlHgSb₄S₇</td>
<td>Rare</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seligmannite</td>
<td>Low-strain, dilational zones</td>
<td>PbCuAsS₃</td>
<td>Rare</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dufrenoysite</td>
<td>Low-strain, dilational zones</td>
<td>Pb₂As₂S₅</td>
<td>Rare</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galkhaite</td>
<td>Low-strain, dilational zones</td>
<td>(Cs,Tl)(Hg,Cu,Zn)₆(As,Sb)₄S₁₂</td>
<td>Rare</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galkhaite</td>
<td>Low-strain, dilational zones</td>
<td>(Pb,Tl)₂₁(As,Sb)₉₁S₁₄₇</td>
<td>Rare</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rathite</td>
<td>Low-strain, dilational zones</td>
<td>(Pb,Tl)₃(As,Sb)₅S₁₀</td>
<td>Rare</td>
<td>Harris (1989)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Native metals and intermetallic compounds</td>
<td></td>
<td></td>
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</tbody>
</table>
Figure 7D a gold grain with relatively Ag and Hg rich margins abuts stibnite, and the zoning is absent adjacent to the stibnite. Aurostibite is commonly associated with gold and native stibnite, as well as with the gold-bearing Tl-sulfosalts, criddleite (TlAgAu2Sb10S10; Harris, 1989). Calaverite (AuTe2) and petzite (Ag3AuTe2) are associated with the other tellurides, as well as with native arsenic, tennantite, realgar, and gold (Harris, 1989).

**Evaluation of Alternative Mobilization Mechanisms**

There are three different mechanisms that may have concentrated precious metals and sulfosalts in dilational structures at Hemlo: solid-state mobilization, dissolution and/or reprecipitation associated with a hydrothermal fluid, or migration of polymetallic melt. In fact, it is likely that all three of these were responsible for some degree of mobilization at Hemlo, although we aim to show that the latter was the dominant mechanism.

Deformation during and after peak metamorphism is expected to have been the driving force for mobilization of precious metals and sulfosalts at Hemlo. In any deforming multiphase medium, some phases deform more easily (are less competent) than others. These mobile phases move down hydraulic gradients that develop between compressional and dilational regions during deformation, to collect in dilational sites. Various authors have noted that many sulfides undergo solid-state mobilization through this process, because they become ductile at lower temperatures than do silicates and so are preferentially transported (see Marshall et al., 2000, for a comprehensive review). Molybdenite is particularly ductile, yet apart from localized concentrations at meso- to microscale fold hinges, there is no evidence for preferential concentration of molybdenite in dilational sites. In fact, because of strain partitioning, molybdenite-rich regions are generally the most highly strained, and molybdenite is abundant in high-strain compressional domains. Some of the other Group I minerals (e.g., pyrrhotite and sphalerite) are also known to be ductile at 600°C, but they only rarely occur in dilational sites. These observations suggest that solid-state mobilization was not responsible for the majority of the sulfide redistribution.

During prograde metamorphism, rocks that contain hydrous minerals undergo a range of metamorphic dehydration reactions. Thus, during peak metamorphism at Hemlo, there would have been some hydrothermal fluid moving through the rock with the capacity to dissolve sulfides and other metallic minerals and mobilize their constituent elements. During deformation, this hydrothermal fluid would be preferentially focused into dilational domains through the same mechanism discussed above. As is shown below, most of the Group II minerals now observed in dilational sites are not stable at peak metamorphic conditions (some assemblages are only stable at very low temperatures of <300°C). Therefore, if hydrothermal mobilization were responsible for the majority of metal redistribution and led to precipitation of the observed sulfosalt mineral suite, it must have taken place after significant cooling from peak metamorphic temperatures. However, not only is there typically little water available during the retrograde portion of metamorphic cycles, the dilational structures where the minerals are located are syn- to late-peak ductile structures (D2 and D3) that were
probably inactive at lower temperatures. Only brittle deformation can proceed at the low temperatures required.

The presence of large amounts of sulfosalt in numerous, relatively small dilational domains would have required large volumes of mobilizing fluids (large fluid/rock ratios) well after peak metamorphism. Although some authors have reported localized silicate alteration associated with retrograde hydrothermal mobilization (e.g., Muir, 2002), the intensity and extent of alteration is less than would be expected to account for the volume of fluid required. At some localities, there is no retrograde alteration assemblage at all (Bodycomb et al., 2000), and relatively high temperature metamorphic phases (e.g., feldspar, kyanite, sillimanite) are closely associated with the mobilized ore minerals. Large amounts of hydrothermal fluid at 300°C or less would have completely destroyed these silicate minerals and would have led to sericite-chlorite-clay assemblages. The paucity of postmetamorphic quartz-carbonate veins associated with mobilized mineralization also argues against a major role for hydrothermal fluids.

In addition, Wood et al. (1987) conducted a series of solubility experiments on the assemblage, pyrite-pyrrhotite-magnetite-sphalerite-galena-gold-stibnite-bismuthinite-argentite-molybdenite, with H$_2$O-NaCl-CO$_2$ solutions from 200° to 350°C. They found that in chloride-free solutions, the relative solubilities follow the sequence Sb > Fe > Zn > Pb > Ag-Mo > Au-Bi. Fe, Sb, and Zn would, therefore, be preferentially mobilized relative to the other elements in a retrograde environment. Although Sb has been extensively mobilized at Hemlo, neither Fe nor Zn is enriched in most dilational sites, whereas Au, Ag, and Pb are.

These factors suggest that hydrothermal mobilization of ore minerals, as suggested by Pan and Fleet (1995), was not...
FIG. 6. Examples of mineralization in dilational domains. A. A sketch (from a series of photomicrographs) of a strongly boudinaged feldspar-quartz layer (unfoliated) within muscovite ore (foliated), showing that stibnite (black) is distributed predominantly at the boudin necks and in extensional fractures in the competent layer. In this sample, disseminated pyrite occurs in the strained muscovite-rich portion and also in the boudinaged layer, but stibnite only occurs within the boudinaged layer and as thin stringers along the high-strain margins. We interpret these thin stringers as migration pathways, where sulfosalts melt migrated before encountering a dilational feature. B. A small accumulation of stibnite (Stb) within a boudinaged K-feldspar-rich layer (Ksp) with radiating fine fractures filled with more stibnite. Elsewhere in this boudinaged layer are additional microfractures filled by realgar and a range of other sulfosalts. C. Edge of the large stibnite-realgar clot in Figure 5 (sample AGT-Hem015e), and an accumulation of the rarer sulfosalts at the periphery. D. Gold in a fracture with native arsenic, tetrahedrite-tennantite (Hg rich), stibnite, and twinnite (sample AGT-Hem003). The composition of the gold in this photomicrograph is plotted in Figure 11C. E. Realgar and rathite exsolutions in stibnite.
the major mechanism of remobilization at Hemlo. Therefore, it is possible that the third mechanism, mobilization of a sulfide melt, was responsible for the majority of ore mineral redistribution at Hemlo. Although there have been very few studies on the viscosity of sulfide liquids, it is known that FeS melt has a viscosity similar to that of water at high temperature and pressure (Dobson et al., 2000). This means that sulfide melts would be highly mobile during deformation and would efficiently migrate toward dilational sites from compressional regions. The remainder of the paper examines phase equilibria and textural evidence that supports this hypothesis.

Phase Relations Relevant to the Hemlo Ore Assemblage

At least 15 elements are components of the ore assemblage at Hemlo (Table 1). No single experimental study resolves the complex phase relations involving cotectics, eutectics, and thermal divides in this system. Most published experimental studies are limited to two- to five-component systems. Therefore, we combined the results of these simple, experimentally determined systems to investigate the possible melting behavior of the Hemlo ore assemblage. The selection of elements considered in each subsection is based on actual ore mineral compositions at Hemlo. Unfortunately, there are many gaps in the experimental studies, and the following discussion also highlights areas for further research.

Melting relations among the sulfosalts in the system Sb-As-Tl-Pb-Ag-Cu-Fe-S

Figure 8 contains a series of binary and ternary phase diagrams for subsets of this system. Although there are many possible subsystems for which there are no experimental data (e.g., those involving realgar), it is clear from Figure 8 that, even as isolated phases (not in contact with other minerals),
many of the sulfosalts minerals at Hemlo would be molten at temperatures well below peak metamorphism. For example, orpiment, realgar, and stibnite melt at 310°, 321°, and 556°C, respectively (Fig. 8A and B). Where minerals coexist, a melt is invariably generated at even lower temperatures. Figure 8B and G shows that when stibnite and orpiment (two common phases at Hemlo) coexist, they initially react as temperature increases to form a solid solution \((\text{Sb,As})_2\text{S}_3\). As temperature increases further, this solid solution starts to melt. Figure 8B shows that in this reaction, As-rich local bulk compositions may produce melt at less than 275°C; and by 556°C, even the most Sb-rich solid solution is completely molten. Figure 8B shows coexisting realgar (AsS) and stibnite, which would likely react at similar conditions, given the similar melting points of realgar and orpiment (Fig. 8A). Nearly all stibnite that we examined microscopically had realgar exsolutions, indicating solid solution between these minerals.

By using phase diagrams determined for pure systems (Fig. 8C and D), it is possible to investigate how interaction among stibnite, the arsenic sulfides, and tetrahedrite-tennantite solid solution (tet-tenss), all common at Hemlo, compared to the other sulfosalts (Harris, 1989), would have produced melt if they all existed prior to peak metamorphism. Note that the end members, tetrahedrite \((\text{Cu}_{12}\text{Sb}_4\text{S}_{13})\) and freibergite \((\text{Ag}_{12}\text{Sb}_4\text{S}_{13})\), are considered to be analogous to skinnerite tet-tenss. As temperature increases, the end members, tetrahedrite and freibergite would have produced melt if they all existed prior to peak metamorphism. Note that we examined microscopically had realgar exsolutions, indicating solid solution between these minerals.

Figure 9 shows that only about 1 to 2 percent FeS is present in sulfosalts melts containing CuS, SbS, AsS, and Pb at 600°C (Fig. 8J). Although there have been no studies that examined ZnS, HgS, or MnS in place of FeS, there is solid solution among these end members. Thus, these components may show behavior similar to that of FeS in the melting reactions. Because addition of HgS to \((\text{Zn,Fe,Mn})\text{S}\) significantly lowers the melting temperature of the solid solution (see also Powell and Pattison, 1997). Of the pure end-member phases, cinnabar has the lower melting point at 825°C (Kullerud, 1965), whereas pure ZnS melts at 1,680°C (e.g., Mavrogenes et al., 2001). Substitution of Zn in cinnabar increases the melting temperature of the solid solution (Osadchii, 1990). There is also potential for CuS, CdS, NiS, SnS, InS, and GaS solid solution in the sphalerite system at 600°C (Czamanske and Goff, 1973; Kojima and Sugaki, 1984; Osadchii, 1986, 1990, 1996; Ueno and Scott, 2002). Electron microprobe analyses of cinnabar-sphalerite exsolution lamellae show that the precursor solid solution contained only minor FeS and MnS (Table 1); and trace amounts of GaS, InS, and CuS are now detected in sphalerite.
The images contain diagrams and data points related to phase diagrams in solid-state chemistry. The diagrams illustrate the changes in temperature and weight percentage or atomic percentage of various elements, such as As, Sb, and S, as they form different phases. The diagrams are labeled with temperature and phase changes, indicating the stability of various compounds and phases under different conditions. The diagrams also include annotations for specific phases, such as FeS, Cu2S, Ag2S, and ZnS, among others. The data points are connected with lines to represent the phase transitions and stability fields.
preferential partitioning of Hg from the solid solution into the melt.

In the subsystem Fe-Mo-S (Fig. 10E), molybdenite and pyrite start to melt at 735°C (at 1 bar). The initial melting temperature clearly exceeds the peak metamorphic temperature reached at Hemlo, so a melting reaction between these two minerals is not expected. Although phase relations between molybdenite and the other sulfides are largely unknown, the paucity of molybdenite in association with Group II minerals suggests that it did not melt at the peak P-T conditions.

Melting relations in the system Au-Ag-Hg-As-Sb (S absent)

All of the components in the Au-Ag-Hg-As-Sb system are present at Hemlo as native elements and/or as intermetallic compounds (such as aurostibite, AuSb2). All gold grains contain Ag and Hg in solid solution, and some of the gold grains lie in the AuAgHg + L field at 600°C (Fig. 11A–C). This means that even in the absence of other minerals, some of the gold grains from Hemlo would have partly melted during peak metamorphism. However, gold grains in the dilational zones typically coexist with many other phases, which further reduce their melting temperature.

Native arsenic rims a large proportion of gold grains in the dilational domains, although the rims are often very narrow (e.g., Figs. 6 and 7). Such grains would react to form gold and a Au-As melt. Or, if there was more than 32 percent As in an Au-As grain (e.g., Fig. 7A), the reaction products would be native arsenic and Au-As melt. Both reactions occur at 636°C in the pure system (Fig. 11D). Although the system Ag-As-Au-Hg has not been studied experimentally, it is probable that significant amounts of Hg and Ag in solid solution in gold would lower the eutectic temperature, possibly resulting in a wide compositional field for melt at 600°C.

Examination of the Au-Sb binary subsystem (Fig. 11E) reveals that native antimony is completely molten at 631°C, and when native antimony and aurostibite (AuSb2) coexist, melting commences at 460°C. In this melting reaction, aurostibite is completely consumed and the melt becomes more Sb rich with increasing temperature. As an isolated phase, aurostibite melts at 460°C, but coexisting aurostibite and pure gold start to melt at only 360°C. Figure 7B and C shows examples from Hemlo of gold (with ~26% Hg and 5–9% Ag in solid solution) coexisting with aurostibite. The assemblage is present in late fractures within a D2-boudinaged quartz vein (i.e., deformed at high temperature), consistent with a Au-rich melt persisting at Hemlo during retrograde cooling down to 360°C or less. At 600°C, a melt containing as much as 85 percent Au can exist in the Au-Sb binary system, indicating that Sb has a profound influence on melting of gold. Addition of Ag, Hg, and As to the Au-Sb system promotes even greater melting of gold. For example, As-Sb binary phase relations (Fig. 11F) show that addition of Sb lowers the melting point of As considerably (and vice versa). These phase relations suggest that at 600°C, only compositions along the Au-As join with little contamination from Hg, As, and Sb (as well as fairly pure native arsenic and antimony) would have remained solid. Therefore, most of the gold associations observed in dilational structures at Hemlo (Figs. 6 and 7) represent assemblages that would have been molten at peak metamorphic conditions.

Melting relations in the system Au-Ag-Hg-Sb-Pb-Ni-Te

The most important part of this system, in terms of understanding gold distribution at Hemlo, is the subsystem Au-Ag-Te, which has been studied extensively by experimentalists. The phase relations show that coexisting gold, calaverite (AuTe2), and petzite (AuAg3Te2; all found at Hemlo) would start to melt below 335°C (Fig. 12), with the specific reactions depending on the starting composition. Figure 12A shows that in isolation, calaverite melts at 464°C; but in association with other phases, the melting temperature can be significantly lowered.

\[ \text{Figure 8: Phase relations among sulfosalts in the system Sb-As-Ti-Pb-Au-Cu-Fe-S at 1 bar. Phases identified at Hemlo are indicated in italics. A. Phase diagram of the system As-S (after Hansen and Aderko, 1958), showing that in isolation, realgar (AsS) and orpiment (As2S3) melt at 321° and 310°C (at 1 bar), respectively: Dashed lines on all diagrams indicate less certainty. B. Phase diagram of the system AsS2-As2S3 (orpiment-stibnite). This diagram was constructed from information in Sobott (1984). C. Phase diagram of the system Cu2S-As2S3 at 1 bar (modified from Bryndzia and Davis, 1989). In this pure system, skinnerite (Cu3SbS3; Tm = 610°C) is analogous to the Cu-tetrahedrite end member (Cu12Sb4S13) in more complex natural systems. D. Phase diagram of the system AgS-As2S3 at 1 bar (after Bryndzia and Kleppa, 1988). In this pure system, pyargyrte (Ag6Sb2S7; Tm = 485°C) is analogous to the Ag-tetrahedrite end member (Ag6Sb2S7) in more complex natural systems. E. Phase diagram of the system PbS-As2S3 at 1 bar (after Salanci, 1979). Path A illustrates the compositional path followed during equilibrium crystallization of a given melt composition. Path B illustrates the compositional path followed by the same melt during ideal fractional crystallization. F. Phase diagram of the system FeS-As2S3. This diagram was constructed from information in Barton (1971), Figure 8J, and Urazov et al. (1983). G. Ternary section in the system AsS2-As2S3-TiS (after Sobott, 1984), showing phase distribution at 315°C (at 1 bar). The lighter-shaded region represents the extent of the liquid field at 275°C. Note that (A) corresponds to the bottom join on this diagram. H. Ternary sections at 500° and 600°C in the system PbS-FeS-As2S3 at 1 bar. The 500°C section is that given by Chang and Knowles (1977) and shows the subsolidus mineral phases in this system. The 600°C section was constructed from information in Chang and Knowles (1977) and Barton (1971). Although we do not know the extent of FeS melting, we suggest that it is likely that FeS contributes minimally to the melt composition, based on (F) and (J). I. Ternary section in the system As-Cu-S (modified from Maske and Skinner, 1971), showing the distribution of mineral phases and melt at 300°C, and the distribution of melt at 500°, 600°, and 665.5°C. A = unnamed compound, Cv = covellite, Dom = domneyite, En = enargite, fcc = face centered cubic, hcp = hexagonal, l.t. = laurite, S = sinnerite. J. Liquidus surface map of the system Fe-Sb-S (after Barton, 1971). All of the fields in the detail to the right are + L2. Note that there is only <1 percent Fe2O3 or FeS in the melt at 600°C. The position of Figure SF on this diagram corresponds to the join between Fe2O3 and Sb2S3, K. Ternary section in the system CuS-PbS- Sb2S3 (after Pruseth et al., 1997), showing the distribution of minerals and melt at 500°C (at 1 bar). L. Ternary section in the system AgS-PbS- Sb2S3 (after Hoda and Chang, 1975), showing the distribution of minerals and melt at 500°C (at 1 bar). The differences between the PbS-Sb2S3 axes of (H), (J), and (K) are due to differences in the published phase diagrams. \]
FIG. S. (Cont.)
As Smelt + pyrrhotite proceeds, increases by 17°C/kbar (Clark, temperature at which the reaction arsenopyrite + pyrite = Mavrogenes et al. (2001) found that the eutectic temperature temperatures, and two experimental studies bear this out. Pressure in S-bearing systems leads to slightly higher melting phase relations. Frost et al. (2002) suggested that increasing makes it impossible to accurately calculate the high-pressure effect of pressure (PbTe) melts at <425°C (Legendre, 1990).

Nearly all of the experimental systems discussed above were determined at atmospheric pressure only, and the inadequacy of thermodynamic data for most of the sulfosalts makes it impossible to accurately calculate the high-pressure phase relations. Frost et al. (2002) suggested that increasing pressure in S-bearing systems leads to slightly higher melting temperatures, and two experimental studies bear this out. Mavrogenes et al. (2001) found that the eutectic temperature of the system FeS-PhS-ZnS increases by 6°C/kbar, and the temperature at which the reaction arseneopyrite + pyrite = AsS_3 + pyrrhotite proceeds, increases by 17°C/kbar (Clark, 1960); although data in Sharp et al. (1985) suggest that the increase may be closer to 14°C/kbar. However, Roland (1968) found that the temperature of the reaction jordanite = galena + Pb-As-S, did not vary with pressure within the uncertainty of measurement.

For Sb-bearing systems, Frost et al. (2002) suggested that increasing P may lead to lower melting temperatures, because the melting temperature of pure Sb decreases with increasing pressure (~0.2°C/kbar; Liu and Bassett, 1986). For the S-absent system Ag-As-Au-Hg-Sb, this may lead to slightly reduced melting temperatures at higher pressures. Similarly, the melting temperature of Sb_3S_5 and the other Sb-sulfosalts may be less affected by pressure than are most other sulfides and sulfosalts, although this has not been experimentally determined. The melting temperature of pure Te is less affected by pressure (1.5°C/kbar) than that of pure S (13.8°C/kbar; Liu and Bassett, 1986), suggesting that melting temperatures of tellurides may be less sensitive to pressure than that of sulfides.

Implications for mobilization

Consideration of published, experimental evidence suggests that the assemblage of ore minerals in the dilational domains (the group II minerals) is consistent with having crystallized from a complex sulfosalt-dominated melt. In contrast, the ore mineral assemblages in the higher strain, compressional domains (the group I minerals) are unlikely to have melted. This implies that sulfosalts melts were mobilized from higher strain regions into dilational sites during syn- to late-peak metamorphism (D_2 and D_3 structures), whereas refractory sulfides were not extensively mobilized. Evidence for localized hydrothermal alteration associated with some dilational sulfosalts-bearing structures (Muir, 2002) is not inconsistent with a melting model, because any hydrothermal fluid present would be expected to migrate to the same structural sites, and perhaps even deposit minor amounts of metal. Based on the amount of sulfosalts minerals in the deposit, we estimate that the sulfosalts melt volume at the peak of metamorphism may have been <2 percent of the rock volume.

Discussion

Praemetamorphic ore mineral assemblage

It is likely that metamorphism and melting significantly modified the premetamorphic ore mineral assemblage. The rare examples of unmetamorphosed ore deposits with bulk geochemistry similar to that of the Hemlo ores (e.g., Lake George: Seal et al., 1988; Nizke Tatry: Chavan et al., 1995) contain pyrite, molybdenite, stibnite, pyrrhotite, arsenopyrite, native antimony, gold, sphalerite, galena, tetrahedrite, bornite, and chalcopyrite. It is likely that many of these minerals, in addition to cinnabar, were present prior to metamorphism at Hemlo. The group I minerals at Hemlo were probably part of this original mineral assemblage. Although it is difficult to rule out that realgar and orpiment were also part of the original mineral assemblage, the presence of arsenopyrite in the unmetamorphosed deposits suggests that it was the important As mineral in the premetamorphic assemblage (orpiment, realgar, and arsenopyrite cannot coexist in equilibrium; Fig. 13). The preservation of arsenopyrite in the wall rocks at Hemlo supports this interpretation (the fate of arsenopyrite during metamorphism is discussed below). The rarer elements may have resided as substitutions in the more common sulfides (e.g., Ag and Tl in galena), or as included rare minerals.
FIG. 10. Phase relations among the refractory sulfides in the system MoS₂-FeS₂-FeS-ZnS-HgS-MnS at 1 bar. Phases identified at Hemlo are indicated in italics. A. Phase relations in the system FeS-ZnS (after Kullerud, 1953), showing the extent of solid solution (at 150 bar). B. Phase relations in the system ZnS-HgS (at 1 bar). This diagram is partly derived from Powell and Pattison (1997), and partly from Osadchii (1990). Note that above ~425°C there is complete solid solution between ZnS and HgS, and that melting commences at the pure HgS end member at 825°C. Cnb = cinnabar, HgSph = mercurian sphalerite, HTss = high-temperature solid solution, LTss = low-temperature solid solution, ZnMCnb = zincian metacinnabar. C. Phase relations in the system ZnS-MnS (after Tauson et al., 1977), showing the extent of solid solution (at 1 kbar). D. Backscattered electron image of phases exsolved from HgS-ZnS-MnS solid solution at Hemlo. E. Phase relations in the system Fe-Mo-S (after Grover et al., 1975). Three ternary sections at 677° to 726°, 735°, and 750°C (all at 1 bar pressure) show the commencement of melting between pyrite (FeS₂) and molybdenite (MoS₂) by the reaction Py + Mo = Po + Mo + L.
FIG. 11. Phase relations in the sulfur-absent system Au-Ag-Hg-As-Sb at 1 bar. Phases identified at Hemlo are indicated in italics. A. Au-Hg phase diagram (after Okamoto and Massalski, 1986a). This diagram corresponds to the bottom join in (C). B. Ag-Hg phase diagram (after Hansen and Aderko, 1958). This diagram corresponds to the right join in (C). C. Au-Ag-Hg ternary diagram constructed from (A) and (B), showing the approximate positions of the solid solution, solid solution + liquid, and liquid fields at 600° and 650°C. Also plotted are compositions of gold grains from this study (open circles), from Harris (1989; closed circles), and from Williams-Jones et al. (unpub. report for Canadian Mining Industry Research Organization, 1998; crosses). The star represents the composition of a gold grain from sample AGT-Hem003, which is shown in Fig. 6D. The range of gold composition in sample AGT-Hem004 (shown in Fig. 7B and C) is also indicated. D. Au-As phase diagram (after Okamoto and Massalski, 1986b). E. Au-Sb phase diagram (after Okamoto and Massalski, 1986c). F. As-Sb phase diagram (after Hansen and Aderko, 1958).
Formation and migration of the sulfosalt melt

Of the original ore mineral suite, we believe that the most important contributors to the melt (in terms of melt volume) were stibnite and arsenopyrite, because Sb- and As minerals are dominant in all dilational domains. The relative abundance of arsenopyrite in the hanging-wall rocks compared to the ore zones suggests that it may have been consumed within the orebody during prograde metamorphism. Melting of stibnite, even as an isolated phase, would have occurred when the temperature exceeded ~556°C (depending slightly on the pressure). However, arsenopyrite melting is dependent on $f_{S_2}$ (e.g., Clark, 1960), which is buffered during prograde metamorphism by a combination of desulfidation reactions and reactions involving silicate minerals (Tracy and Robinson, 1988; Seal et al., 1990; Craig and Vokes, 1993). The persistence of pyrite throughout the deposit indicates that $f_{S_2}$ must have been high at peak metamorphic conditions, beyond the stability field of arsenopyrite, and that arsenopyrite melting is a reasonable possibility (Fig. 13). This melting would have proceeded by two possible reactions:

1. $\text{FeAsS} + \text{FeS}_2 = \text{As-S}_{(\text{liquid})} + 2\text{FeS}$
2. $\text{FeAsS} + S_2 = \text{As-S}_{(\text{liquid})} + \text{FeS}_2$

Reaction 1 takes place on the pyrite-pyrrotite buffer and results in the formation of pyrrhotite as a solid by-product. Therefore, the occurrence of this reaction would be recorded by the presence of pyrrhotite in the final assemblage, but in fact pyrrhotite is only locally observed. Reaction 2 implies the consumption of some other S-bearing mineral, liberating S. Of the two other widely distributed S-bearing minerals at Hemlo (molybdenite and barite; Harris, 1989), only barite is likely to have been consumed during metamorphism. Most of
the widely distributed barian K-feldspar grains at Hemlo show consistent concentric zoning with wide low-Ba cores and high-Ba margins (Fig. 4C). These typically display a granoblastic texture with ~120° triple junctions, suggesting additional metamorphic growth and equilibration in a Ba-enriched environment. This implies that barite was consumed during metamorphism at Hemlo, thus releasing S for arsenopyrite melting by reaction 2.

An As-Sb-S melt would have been highly mobile during deformation due to its low viscosity. This would have enabled it to physically and chemically interact with the other ore minerals (by wetting grain boundaries), promoting further partial melting. Some elements, such as Hg, Ag, and Tl, may have partitioned into the melt from refractory solid-solution phases (e.g., Frost et al., 2002). The fact that many of the group II sulfosalts contain significant Hg, but little Fe or Zn, suggests that Hg was preferentially partitioned into the melt.

During equilibrium crystallization, each aliquot of melt would crystallize a relatively simple assemblage (e.g., path A; Fig. 8E). However, during fractional crystallization, melts would evolve toward eutectic compositions and continually crystallize additional phases (e.g., path B; Fig. 8E). In this way, fractional crystallization, induced by late episodes of deformation (probably associated with D3, D4, and D5), may have led to the very low melting-temperature mineral associations. With more components, the array of possible crystallization paths is multiplied, consistent with the large range of assemblages observed. This would account for the late realgar-coated fractures and the array of rare sulfosalt phases in fractures propagating from coarse stibnite and/or realgar clots (Figs. 5 and 6).

Because the melt volume was low, there was limited interconnectivity between individual melt accumulations. Each accumulation would therefore have been internally buffered and controlled by the immediate bulk-rock composition. It is possible to predict cooling paths for simple assemblages. During equilibrium crystallization, each aliquot of melt would crystallize a relatively simple assemblage (e.g., path A; Fig. 8E). However, during fractional crystallization, melts would evolve toward eutectic compositions and continually crystallize additional phases (e.g., path B; Fig. 8E). In this way, fractional crystallization, induced by late episodes of deformation (probably associated with D3, D4, and D5), may have led to the very low melting-temperature mineral associations. With more components, the array of possible crystallization paths is multiplied, consistent with the large range of assemblages observed. This would account for the late realgar-coated fractures and the array of rare sulfosalt phases in fractures propagating from coarse stibnite and/or realgar clots (Figs. 5 and 6).

Because the interpreted bulk composition of melt accumulations at Hemlo was dominated by antimony, stibnite is likely to have crystallized early. However, because all sulfosalts melts are likely to have been saturated in FeS2, very small amounts of pyrite, berthierite, or pyrrhotite are expected to have been the first phases to crystallize in most instances. As crystallization of stibnite progressed, the remaining melt would have become enriched in the other elements. Arsenic also was likely abundant in the melt, but Figure 8B indicates that arsenic must be extremely enriched in the melt before realgar or orpiment could be the first to crystallize. Therefore, most sulfosalts melt accumulations are likely to have evolved toward Sb-poor and As-rich compositions. This explains why realgar is common in the last stages of mobilization. The remaining melt would have become enriched in the other elements. Arsenic also was likely abundant in the melt, but Figure 8B indicates that arsenic must be extremely enriched in the melt before realgar or orpiment could be the first to crystallize. Therefore, most sulfosalts melt accumulations are likely to have evolved toward Sb-poor and As-rich compositions. This explains why realgar is common in the last stages of mobilization.
we suggest the following order of depletion from the melt (or order of crystallization) for most sulfosalt melt accumulations at Hemlo: Zn → Fe → Hg → Sb → Pb → Ag → Cu → As → Tl. Although Hg and Sb may be depleted early in the sequence, enough must have remained in the melt to account for the high Hg and Sb content of the Tl-bearing sulfosalts at Hemlo (Fig. 8G). Gold is likely to have continually crystallized during cooling, down to temperatures slightly lower than 335°C (Figs. 11 and 12).

Implications for mining and exploration at Hemlo

An anuriferous sulfosalt melt, like any ore-bearing fluid, would be expected to have migrated along the Hemlo shear zone and not away from it (north or south). Fluids within shear zones are preferentially focused into dilational regions, such as jogs, and they are mainly expelled at the terminus of the shear zone or at splays, rather than escaping laterally into the wall rocks (e.g., Cox et al., 2001).

We have shown that pockets of sulfosalt melt were likely trapped at meso- and microscale dilational sites up to 1.5 m in size. Larger-scale features (meter to hundreds of meters) into which greater volumes of melt could have migrated might also have been present. Prospective structures within or close to the mineralized zone would therefore include megaboudins within larger competent units (such as premetamorphic dikes), fault-related jogs in the contact between the metasediments and the Moose Lake phorphy, and perhaps the hypothetical saddle between these same units in the nose of the isoclinal fold proposed by Lin (2001). This last structure, if it existed, may have been destroyed by progressive shear, as is commonly observed in isoclinal fold systems.

The low viscosity of sulfide melts means that they could potentially migrate long distances (tens of kilometers). However, the predicted volume of melt at Hemlo was small (<2% of the rock volume), and there are a large number of small dilational domains within the rock volume, so it is possible that most of the melt only migrated a short distance to the nearest dilational site. In this way, we suggest that the process of sulfide melting at Hemlo may have produced a nugget effect, where small pockets of very high grade gold are dispersed within large volumes of average-grade ore material.

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HEMLO GOLD DEPOSIT: MELTING OF A PRECIOUS METAL-SULFOSALT ASSEMBLAGE


