### Genesis and metamorphism of the Hemlo gold deposit, Ontario

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### **Thesis Abstract**

The worldclass Hemlo deposit is one of Canada's largest gold producers, containing 95 million tons of ore grading ~8 g/t Au; the mineralization is hosted mainly by two sub-parallel shear zones. However, unlike most Archean lode gold deposits, the ore occurs as finely disseminated Hg- and Ag-bearing native gold in potassically altered rocks, and is associated with molybdenite, stibnite and realgar.

Mineralization occurred at greenschist conditions (400 to 500°C), and was subsequently overprinted by a single metamorphic event that peaked at ~630°C and 5 to 7 kb, which recrystallized the ore and alteration assemblages. Retrograde cooling lasted for ~80 m.y., with temperature decreasing on average ~5°C per m.y. Ore formation involved three reactions that affected  $fS_2$ ,  $fO_2$ , and pH: the dissolution of sedimentary barite, the precipitation of pyrite, and the replacement of muscovite by Kfeldspar. During sulfidation, caused by the dissolution of barite, iron partitioned preferentially into pyrite, which prevented the formation of Fe-bearing metamorphic index minerals (such as garnet and staurolite), oxides (e.g., magnetite, hematite, ilmenite), and low-fS<sub>2</sub> sulfides (e.g., pyrrhotite). In addition, K-alteration strongly enriched the ore zones in K-feldspar (microcline) and muscovite, which buffered pH, and prevented formation of aluminosilicates. Hemlo is an example of a mesothermal deposit which formed from metamorphic fluids with a significant magmatic component. Deposition of native gold and molybdenite occurred due to decreases in pH and  $fO_2$  that accompanied potassic alteration and pyrite precipitation. Other elements, such as Sb and As were adsorbed initially onto pyrite growth surfaces. Near peak metamorphism, the deposit evolved a sulfide melt that formed through release of As and Sb from pyrite during metamorphic recrystallization, partial decomposition of primary minerals (such as native gold), and interaction of the melt with sulfur-bearing aqueous metamorphic fluids. The mineral assemblages that crystallized from this melt are similar to those predicted by experimental data for the As-Sb-S and related systems, and are interpreted to have formed by fractional crystallization.

### Résumé de thèse

Le gisement de renommée mondiale Hemlo figure parmi les plus grands producteurs d'or au Canada, avec ses 95 millions de tonnes de minerai ayant une teneur de  $\sim 8$  g/t Au; la minéralisation est principalement incluse dans deux zones de cisaillement sous-parallèles. Toutefois, à la différence de la plupart des gisements archéens d'or filonien, le minerai se présente comme de l'or natif (renfermant du Hg et de l'Ag) finement disséminé dans les roches altérées par le potassium et il est associé avec la molybdénite, la stibnite et le réalgar.

La minéralisation s'est produite dans les conditions du faciès des schistes verts (400 à 500°C) et a subséquemment été surimposée par un seul épisode métamorphique qui a culminé à ~630°C et 5 à 7 kb, et qui a recristallisé le minerai et les minéraux d'altération. Le refroidissement rétrograde a duré ~80 m.y., avec une baisse moyenne de la température de ~5°C par m.y. La formation du minerai a donné lieu à trois réactions qui ont affecté le  $fS_2$ , le  $fO_2$  et le pH: la dissolution de la barite sédimentaire, la précipitation de la pyrite et la substitution de la muscovite par le feldspath-K. Lors de la sulfidation, causée par la dissolution de la barite, le fer s'est divisé de façon préférentielle en pyrite, ce qui a empêché la formation de minéraux à indice métamorphique ferrifère (tels le grenat et la staurolite), des oxydes (p.ex. la magnétite, l'hématite, l'ilménite) et des sulfures à faible teneur en S<sub>2</sub> (p.ex. la pyrrhotite) De plus, l'altération-K a fortement enrichi les zones de minerai en feldspath-K (microcline) et muscovite, qui ont tamponné le pH et empêché la formation des silicates alumineux. Hemlo constitue un exemple d'un gisement mésothermal qui s'est formé à partir de fluides métamorphiques renfermant une composante magmatique importante. Le dépôt

de l'or natif et de la molybdénite s'est produit en raison de la diminution du pH et du  $fO_2$  qui a accompagné l'altération potassique et la précipitation de la pyrite. D'autres éléments, comme le Sb et l'As ont été adsorbés au départ sur les surfaces de croissance de pyrite. Près du pic du métamorphisme, le gisement a forgé une lave sulfurée qui s'est formée par la libération de l'As et du Sb de la pyrite durant la recristallisation métamorphique, la décomposition partielle des minéraux primaires (comme l'or natif) et l'interaction de la lave avec les fluides métamorphiques aqueux sulfurifères. Les assemblages minéralogiques qui ont cristallisé de cette lave sont similaires à celles calculées par les données expérimentales pour l'As-Sb-S et les systèmes reliés et sont interprétées comme s'étant formées par cristallisation fractionnelle.

### Acknowledgements

My sincere thanks go to my supervisor, Dr. A.E. Williams-Jones (Willy), for his enthusiasm, patience, encouragement and assistance in completing this thesis. Many other people provided technical expertise, access to mine sites, field assistance, and/or participated in inspiring discussions of Hemlo-related and economic geology topics. Glenn Poirier and Jim Clark provided help with electron microprobe and X-ray diffraction analyses. Field work was greatly facilitated by Venetia Bodycomb, who also provided unpublished bulk rock geochemical data. Artas Migdisov and Charles Normand provided invaluable assistance with mineral chemistry and thermodynamic modeling using SUPCRIT and HCh/UNITHERM codes. The staff and operating companies of the David Bell (Teck-Cominco, Barrick-Homestake), Golden Giant (Newmont), and Williams (Teck-Cominco, Barrick-Homestake) mines are gratefully acknowledged for property access and logistical support. This thesis profited from stimulating discussions on many aspects of economic geology with Charles Normand, Artas Migdisov, Sandy Archibald and Katherine Ault. Jim Clark merits special recognition for providing unpublished mineralogical data, many stimulating discussions about Hemlo in particular, and economic geology in general, and reviewing manuscripts.

And finally, I would like to thank my family, whose appreciation of rocks is mostly limited to their use as projectiles or gardening tools, but who were there with much needed moral support. Financial assistance for this thesis was provided CAMIRO, NSERC and FQRNT grants to AEWJ. Additional support was provided by a SEG student grant to M.H.

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# Chapter 1

# **General Introduction**

#### Preface

### **Rationale and objectives**

The enigmatic Hemlo deposit is one of Canada's largest gold producers, but despite numerous studies by government-, industry- and university-based researchers, there is no consensus on the nature of the mineralization, the origin of precursor lithologies, or even whether it formed prior to, during or after regional metamorphism. The general objective of this thesis is to address the effects of regional metamorphism on the deposit, and to constrain the origin of mineralization. Metamorphism destroyed most primary features associated with mineralization, such as fluid inclusions and original ore and alteration assemblages, recrystallized precursor lithologies, locally remobilized mineralization, obscured timing relationships, and therefore lies at the root of many controversies surrounding the genesis and evolution of the deposit. Because of the importance of this poorly understood metamorphic overprint, there is no consensus on the number of prograde metamorphic episodes, the peak metamorphic conditions, the importance of retrograde events, or the relationship between mineralization and metamorphism.

The research presented in this thesis began as part of a multidisciplinary CAMIRO (Canadian Mining Industry Research Organization) research project entitled 'Finding the next Hemlo: defining the parameters'. The project provided unprecedented access to the Hemlo gold deposit, which is exploited simultaneously by three different mines, and integrated detailed research on geology/geochemistry (McGill University), geophysics (McMaster University), structure (GSC/University of Waterloo), and geochronology (ROM, University of Toronto). Additional work by the Ontario Geological Survey, aimed to provide a regional framework, contributed detailed geological maps (T.L. Muir), an analysis of regional structure, stratigraphy and metamorphism (S.L. Jackson), and a study of the petrogenesis of granitoid intrusive rocks (G.P. Beakhouse). Although the research presented in this thesis focuses directly on the genesis and metamorphic evolution of the Hemlo gold deposit and is thus independent of the other studies, it profited greatly from conclusions and interpretations advanced by all the scientists in the CAMIRO project.

### Thesis organization

This thesis is divided into six chapters: a general introduction, four manuscripts and the conclusions/contributions to knowledge.

Chapter II discusses the evolution of the Hemlo gold deposit during prograde metamorphism. In contrast to the metasedimentary rocks, the alteration zones commonly contain significant proportions of sulfides and/or sulfates, and these minerals influence and/or participate in metamorphic reactions. Interaction between sulfates, sulfides, oxides and silicates, or compositional changes such as the addition of S and K during mineralization and potassic alteration, were modeled thermodynamically and used to predict the evolution of hydrothermally altered rocks during metamorphism. This explains apparently contradictory features such as the lack of most metamorphic index minerals in the ore zones, which may help identify metamorphosed alteration zones and aid exploration for similar deposits elsewhere.

Chapter III re-evaluates the P-T-t evolution of the Hemlo gold deposit. Previous metamorphic studies at Hemlo proposed differing/contradictory

interpretations regarding the conditions of peak metamorphism, the number of prograde metamorphic episodes, the importance of retrograde metamorphism, and the relative timing of metamorphism and mineralization. This chapter introduces new geothermobarometric data from wallrocks in the deposit area, and from regional exposures. These data show that mineral assemblages in the vicinity of the ore zones did not preserve peak metamorphic conditions as a result of diffusion and post-peak metamorphic re-equilibration. Relative timing relationships, derived from mineral equilibria and textural constraints, were correlated with geochronological data and expanded into a P-T-t path for the Hemlo area.

Chapter IV investigates the genesis of the Hemlo gold deposit. Although regional metamorphism destroyed primary features (such as fluid inclusions and ore assemblages), the mineralizing conditions can be constrained by textural and geochemical considerations, and thermodynamic modeling. These data indicate that ore zone conditions were controlled by three important equilibria that control pH,  $fO_2$  and  $fS_2$ , namely, the dissolution of sedimentary barite, the precipitation of pyrite, and the replacement of muscovite by K-feldspar. In addition, geological and thermodynamic constraints on mineralization are compared to current genetic models for lode gold mineralization in Archean rocks, and integrated into a generally applicable genetic model.

Chapter V discusses the post-peak metamorphic evolution of mineralization, and evaluates the role and extent of remobilization. Appreciable native gold is intergrown with sulfides such as realgar and stibnite that have upper thermal stabilities below the temperature of peak metamorphism, and therefore must be the products of

remobilization. Gold is also locally hosted by late-stage calc-silicate altered rocks, which previously have been interpreted to have formed as part of an important mineralization event. The research presented in this chapter investigates the importance of these gold associations, remobilization mechanisms, and describes how the deposit was modified mineralogically and genetically during retrograde cooling.

### Contributions of authors

This thesis contains four manuscripts which are coauthored by Prof. A.E. Williams-Jones and J.R. Clark. Professor Williams-Jones provided general thesis supervision and critically reviewed manuscripts, while J.R. Clark supplied unpublished mineralogical data, and reviewed drafts of the manuscripts. However, the scientific interpretations and ideas presented in the papers are, for the most part, those of the first author. In addition, all fieldwork, petrography, geothermobarometric calculation, fluid inclusion work, thermodynamic modeling, and most microprobe analyses presented in these manuscripts were conducted by the first author.

### Introduction

The Hemlo gold deposit, located in north-central Ontario, is one of Canada's largest gold producers, and is exploited by the David Bell, Golden Giant and Williams mines. The deposit contains 95 million tons of ore, with an average grade of  $\sim$ 8.0 g/t Au (Schnieders et al., 2000), and occurs in several zones. The most important of these is the Main ore zone, which is 3 to 45 m wide, and extends over a length of more than 3.7 km and to a depth of at least 1500 m (Muir, 2002). Most of the mineralization is

shear-hosted, and occurs primarily as disseminated native gold near the contact between quartz-feldspar porphyry, barite-rich and metasedimentary rocks. The bariterich rocks have been interpreted to be sedimentary (Cameron and Hattori, 1985; Valliant and Bradbrook, 1986; Burk, 1987; Kuhns, 1988; Thode et al., 1991), or hydrothermal in origin (Harris, 1989; Johnston, 1996). The dominant alteration is potassic, and is characterized by a central zone of granoblastic microcline-quartz-(barite-muscovite-biotite-pyrite) rocks, surrounded by muscovite-quartz-pyrite schists (e.g., Harris, 1989).

### **Literature Review**

### Previous work on Hemlo

### Genetic models

Many genetic models have been proposed for Hemlo, most of which can be shown to be inconsistent with at least some geological and geochemical features of the deposit. Some early studies proposed epithermal hot spring (Goldie, 1985) and exhalative seafloor (Valliant and Bradbrook, 1986) origins for the deposit. However, these models did not account for features such as the extensive potassic alteration, the strong enrichment in Mo, and the discordant relationships between ore zones and host lithologies. A skarn model (Pan and Fleet, 1992) was proposed to account for local calc-silicate alteration, and was later modified to a late-stage (post-peak metamorphic) replacement origin (Pan and Fleet, 1995) that encompassed elements of porphyry, shear and skarn models. However, alteration at Hemlo is dominantly potassic, and is overprinted only locally by late-stage calc-silicate alteration. Since the ore zones are extensively recrystallized and were subjected to ductile deformation, mineralization cannot be considered to be post-metamorphic (cf. Williams-Jones et al., 1998). Most genetic models for Hemlo include elements of mesothermal-shear zone and porphyry/intrusion-related models. A shear zone origin is favored by many researchers (Burk et al., 1986; Hugon, 1986; Corfu and Muir, 1989b; Muir, 1993, 1997) because of the strong structural control on mineralization. However, Hemlo differs from most Archean shear-related deposits as it lacks carbonate/albitic alteration, mineralization is disseminated rather than vein-hosted, and there was significant enrichment of Mo. Support for porphyry-related models (Walford et al., 1986; Kuhns, 1988, Kuhns et al., 1994; Johnston et al., 1995; Johnston, 1996) include the association of gold with molybdenite and the potassic alteration, but there is no known porphyry-type intrusion in the immediate area. Modified porphyry and intrusion-related models (Kuhns, 1988; Kuhns et al., 1994, Williams-Jones et al., 1998) have invoked a granodioritic, calcalkaline intrusion located at some unknown depth below the deposit as the source for the mineralizing fluid. Most recently, Muir (2002) described Hemlo as an "atypical, mesothermal-orogenic, disseminated-replacement-stockwork deposit", emphasizing the complex nature of mineralization.

### Metamorphism

Early metamorphic studies concluded that the Hemlo area was subjected to peak metamorphic (M1) temperature and pressure conditions of ~585°C and ~7 kb (Burk et al., 1986; Burk, 1987), or 500 to 600°C and 4 to 6.5 kb, (Kuhns, 1988; Kuhns et al., 1994). These studies also postulated a less important, second metamorphic event

(M2) based on the occurrence of reversely-zoned garnet, actinolitic/tremolitic rims on prograde hornblende, the presence of minor chlorite and epidote, and the occurrence of fibrolite. Burk et al. (1986) interpreted M2 to reflect prograde metamorphism at lower pressure (5 kb) but similar temperature to M1, due to rapid uplift and erosion, and noted that M2 may have been continuous with M1. By contrast, Kuhns et al. (1994) attributed M2 to intrusion of the Cedar Creek stock, an event which has subsequently been interpreted to have occurred synchronously with or even preceding M1 metamorphism (Corfu and Muir, 1989a; Muir, 2002; Davis, 1998; Davis and Lin, 2003). However, Kuhns et al. (1994) also considered the possibility that M2 might represent retrograde M1 metamorphism, caused by resetting of mineral equilibria due to late-stage fluid infiltration. Estimated P-T conditions for M2 vary from 585°C and 5 kb (Burk et al., 1986), to 300 to 400°C and 1 to 3 kb (Kuhns et al., 1994).

The strongest proponents of a metamorphic history involving two clearly separate prograde events were Pan and Fleet (1993), who based their conclusions largely on data from the White River area, located 10 to 15 km southeast of Hemlo. They estimated pressure-temperature conditions of the first prograde event at 500°C and 6 to 6.5 kb, and those of M2 as 520 to 650°C and 3 to 5 kb. Two prograde events were proposed because of the presence of andalusite, sillimanite and kyanite, and a P-T path derived from a single zoned garnet porphyroblast with mineral inclusions. Pan (1990) suggested that the occurrence of andalusite and sillimanite was indicative of Buchan zone metamorphism (low P, defined by the index minerals staurolite, cordierite, andalusite and sillimanite), and concluded that kyanite (the high-P Al<sub>2</sub>SiO<sub>5</sub> polymorph) was the metastable remnant of a previous metamorphic event (M1).

Multiple metamorphic episodes for the Hemlo region were also proposed by Muir (1997), who interpreted textural relationships among index minerals to be consistent with three metamorphic episodes. However, this latter study did not include thermobarometric calculations, and therefore did not define peak metamorphic conditions.

Powell et al. (1999) postulated a single metamorphic event based on the interpreted occurrence of two generations of andalusite, which they argued were separated by the development of kyanite and then sillimanite. They estimated peak metamorphic conditions to have been 600 to 650°C and 6 to 7 kb from petrogenetic grid constraints (the staurolite-out reaction), and recalculation of the geothermobarometric data of Burk (1987).

### Relative timing relationships

Considering the size and importance of the Hemlo deposit, and the number of previous studies, it is perhaps surprising that there is little agreement on the relative timing of mineralization and peak metamorphism. Studies that favor a pre- to syn-peak metamorphic timing for the mineralization generally emphasize the fact that alteration, which is associated with the main mineralization event (predominantly potassic alteration), was recrystallized during peak metamorphism (Burk et al., 1986; Kuhns et al.; 1994; Michibayashi, 1995; Muir, 1997, 2002; Powell et al., 1999; Williams-Jones et al., 1998; Bodycomb et al., 2000; Lin, 2001). Furthermore, recent studies have also used combinations of structural and geochronological data to support a proposed prepeak metamorphic timing of mineralization (Muir, 2002; Davis and Lin, 2003). On the

other hand, the local association of gold with calc-silicate alteration, the occurrence of apparently low temperature sulfides (e.g., realgar, stibnite, zinkenite) with thermal stabilities below that of peak metamorphism and the lack of metamorphic index minerals in the ore zones, have been used as evidence for a post-peak metamorphic timing (Walford et al., 1986; Hugon, 1986; Pan and Fleet, 1992, 1995; White and Barnett, 1990).

### Remobilization of metals

Studies concluding that mineralization at Hemlo occurred prior to peak metamorphism generally have interpreted the spatial association of gold and low temperature minerals to result from remobilization of primary ore (e.g., Kuhns 1988; Williams-Jones et al. 1998; Powell and Pattison, 1997; Tomkins et al., 2003, 2004; Heiligmann et al., 2003). For example, Williams-Jones et al. (1998) noted that ore-related elements such as antimony and arsenic are highly soluble at amphibolite-facies metamorphic temperatures, and suggested that they could have been remobilized by syn- to post-peak metamorphic fluid infiltration, and deposited in quartz and later stage calc-silicate veins that cut the deposit. An alternative explanation, suggested by Powell and Pattison (1997), was that low temperature sulfide minerals were produced by post-peak metamorphic exsolution from a hypothetical main stage As-Hg-Cu-Zn-Fe-bearing antimonian sulfosalt. According to this explanation, this sulfosalt decomposed, with decreasing temperature, by sequentially exsolving Hg-Zn, Hg-Tl and Hg-Cu sulfides, which in turn exsolved cinnabar, Hg-sphalerite, chalcopyrite and aktashite (Powell and Pattison, 1997). After expulsion of these phases, the remaining solid would have been

a solid solution of stibnite and orpiment, from which orpiment was later exsolved, leaving pure stibnite or stibnite with a low As content. Realgar is interpreted to have formed at the expense of orpiment during a late retrograde event that mobilized finegrained cinnabar, realgar and native antimony along fractures and grain boundaries (Powell and Pattison, 1997). Finally, Tomkins et al. (2003; 2004) and Heiligmann et al. (2003) proposed that low temperature sulfide minerals were the product of a sulfide melt that formed during peak metamorphism. During deformation, this melt migrated into dilational domains such as boudin necks and extensional fractures, and progressively crystallized a suite of minerals including stibnite, realgar, sulfosalts, intermetallic compounds and tellurides.

### Metamorphism of ore deposits

Metamorphic rocks comprise large areas of the world's continental crust and host a range of ore deposit types. If mineralization occurred prior to or during metamorphism, then these deposits were likely modified to some extent by metamorphic-deformational events, and are generally referred to as 'metamorphosed ore deposits' (Vokes, 2000). By contrast, ore deposits that formed directly by metamorphic processes are generally referred to as 'metamorphic, or 'metamorphogenic' deposits (e.g., Vokes, 2000; Marshall et al., 2000). However, the distinction between these processes is not always clear, as deformation, recrystallization and remobilization may obscure timing relationships and depositional models (Vokes, 2000).

One of the earliest accounts of the effects of contact metamorphism on sulfide ores was that of Stevenson (1937, reported in Vokes, 2000), who interpreted the change of pyrite-chalcopyrite to pyrrhotite-chalcopyrite-cubanite near the contact with a camptonite intrusion (Eustis mine in Quebec) as resulting from contact (thermal) metamorphism. The effect of regional metamorphism on banded iron formations was studied by James (1955), who observed that mineral assemblages vary systematically with metamorphic grade. Later studies focussed mainly on sedimentary iron and manganese oxide deposits (e.g., Roy, 1966; Klein, 1973, French 1968), or base metal mineralization (e.g., Banno and Kanehira, 1961; Schreyer et al., 1964; Kinkel, 1967; Vokes, 1976; McClay, 1983), and traced the changes and modifications of volcanichosted massive sulfide deposits from non-metamorphic occurrences to their metamorphosed equivalents in high-grade (e.g., amphibolite facies) metamorphic terranes.

The effects of metamorphism-deformation on pre-existing mineralization can result in changes in fabric (increase in grain sizes, development of specific morphology, modification due to brittle or ductile deformation), changes in mineralogy, remobilization of pre-existing element concentrations, or changes in the structure and morphology of ore bodies. Mineralogical changes during metamorphism include compositional modifications such as the formation of zincian staurolite, the exsolution of less-compatible substituted elements during metamorphic recrystallization (e.g., pyrite exsolves As, Sb and Au during recrystallization; e.g., Tarnocai et al., 1997), and temperature-dependent changes in the compositions of pyrrhotite, sphalerite and arsenopyrite during metamorphism (e.g., Vokes, 2000). Despite these changes, it is not possible to establish a series of sulfide mineral facies, corresponding to those established for silicates and calc-silicates, due to the large stability fields of the common sulfide minerals and the relatively simple chemical compositions of most ores. In addition, high temperature sulfides often re-equilibrate to low temperature assemblages and mineral compositions during retrograde metamorphism. For example, closed system cooling of coexisting pyrite and pyrrhotite results in the formation of pyrite at the expense of pyrrhotite, thereby considerably altering the FeS activity of the remaining pyrrhotite. By contrast, the presence or absence of monoclinic pyrrhotite and/or marcasite may indicate open system behavior and gain or loss of sulfur, which also affects the composition of the pyrrhotite. As a consequence, ore minerals are generally not very useful geothermobarometers. The

sphalerite geobarometer (e.g., Scott and Barnes, 1971; Scott, 1973), based on the assemblage sphalerite-pyrite-hexagonal pyrrhotite, can only be used if equilibrium conditions are preserved. As this assemblage re-equilibrates readily during cooling and by interaction with other minerals, Hutchison and Scott (1981) suggested that only sphalerite poikiloblastically encapsulated in pyrite should be used in order to avoid the effects of Cu on mineral equilibria. A mineral commonly used for geothermometry in rocks metamorphosed to greenschist and lower amphibolite facies conditions is arsenopyrite (e.g., Clark, 1960; Kretschmar and Scott, 1976). However, the effects and importance of pressure and solid solution on equilibrium compositions remain obscure, and it has been recommended that further study be undertaken before this geothermometer can be applied with confidence (Sharp et al., 1985).

One of the most commonly cited effects of metamorphism on sulfide mineralogy is the conversion of pyrite to pyrrhotite ( $\pm$ pyrite) (e.g., Gammon, 1966; Thompson and Norton, 1968; Mookherjee and Suffel, 1968; Mookherjee, 1970), which has been successfully correlated with increasing metamorphic grade in some areas (Ferry, 1981; Runyon and Misra, 1985). The transformation of pyrite to pyrrhotite results in an increase in sulfur fugacity, which, in turn, may cause mineralogical changes such as a decrease in the Fe content of sphalerite (Barton and Toulmin, 1966), transformation of chalcopyrite to bornite + pyrite, and the formation of new pyrite from pyrrhotite and ferromagnesian minerals (Mookherjee and Suffel, 1968; see below).

### Sulfidation and oxidation

An important factor in the metamorphism of ore deposits concerns the participation of sulfide and oxide minerals in the evolution of silicate assemblages through a series of sulfidation and oxidation reactions. Although researchers have been aware of the effects of sulfides on the evolution of silicates during metamorphism for over 40 years, few studies have investigated these changes in detail (Spry, 2000). Early studies (e.g., Marmo, 1957) noted that biotite co-existing with pyrrhotite is more Mg-rich than biotite in sulfide-free pelites, and attributed the Mg-enrichment to a reaction in which Fe from biotite reacts with sulfur to form pyrrhotite. Similar studies of metamorphosed massive sulfide deposits and iron formations showed that variations in the Fe/(Fe+Mg) ratios of silicate minerals depend on equilibria with associated Febearing oxides (hematite, magnetite, ilmenite) and sulfides (pyrite, pyrrhotite) (e.g., Fullagar et al., 1967; Froese, 1969; Hutcheon, 1979; Peterson, 1984; Nesbitt, 1986a, b; Rosenberg et al., 1996; Spry, 2000 and references therein). These findings have been supported and complemented by sulfidation experiments (e.g., Kullerud and Yoder, 1963; 1964), and thermodynamic modeling of phase equilibria (e.g., Froese, 1971, 1976, 1977; Froese and Berman, 1994).

### Remobilization

Metamorphosed ore deposits may be remobilized by a wide range of mechanisms including solid-state transfer, liquid-state transfer, or remobilization by sulfide melts. Solid-state processes include small scale processes such as dislocation flow, and have been used to explain healing of fractures and the formation of low

competence pressure fringes on porphyroblasts (e.g., Vokes, 1969; Presquera and Velasco, 1993), and large scale processes such as transposition by folding and thrusting (e.g., Marshall and Gilligan, 1993). These large scale processes are characterized by extensive modification of mineralization and host rocks, and may dismember and thereby downgrade deposits (Marshall et al., 2000), or concentrate ores into dilational zones such as thrust-associated hinge-zone located shoots (e.g., Juve, 1974; Cook et al., 1993).

Most remobilization mechanisms, however, involve a liquid, which is typically hydrothermal, and may include: (1) deeply circulated meteoric water (e.g., Nesbitt and Muehlenbach, 1989); (2) liquid derived from the low temperature physical and chemical dewatering of the basinal sedimentary sequences (e.g., Mookherjee, 1976); (3) liquid derived from metamorphic dewatering during orogenesis (e.g., Fyfe et al., 1978; Etheridge et al., 1983); and (4) liquid exsolved from cooling silicate magmas (e.g., Wyllie, 1983). Such liquids may dissolve ore metals and remobilize deposits, if time-integrated fluid fluxes are sufficiently high, and if metals can be precipitated efficiently elsewhere (Marshall et al., 2000). In structurally-hosted gold deposits, fluid flow may be pervasive or channeled (e.g., Etheridge et al., 1983; Oliver, 1986) and can significantly remobilize primary mineralization. Pervasive flow generally occurs around grain boundaries, and through microcracks that open due to fluid overpressure. If fluid migration is dominated by advective transport along fractures, it is generally considered channeled; although the process is partly scale dependent, fluid flow in shear zones can be pervasive on a meter-scale, or on a kilometer-scale the shear zone may act as a channel (Marshall et al., 2000). Marshall and Gilligan (1987) and
Marshall et al. (2000) considered that the importance of fluid-driven remobilization on massive sulfide ore deposits is likely to be minor as these bodies are generally not very permeable, and fluids only infiltrate during discrete episodes such as deformational events. By contrast, in shear zone-hosted gold deposits, fluid infiltration may disperse mineralization widely.

## Remobilization by sulfide melt

Very few studies have proposed the formation of sulfide melts during metamorphism. Partial melting of ore assemblages was first suggested for the Broken Hill Pb-Zn deposit of Australia (Lawrence, 1967) and the Bleikvassli Zn-Pb deposit in Norway (Vokes, 1971). However, these interpretations did not find widespread acceptance, as field and textural evidence was ambiguous, and relevant experimental work was not representative of geologically realistic conditions (cf. Plimer, 1987; Skinner and Johnston, 1987). On the other hand, unrelated experiments (e.g., Craig et al., 1974) have shown that As- and Sb-bearing assemblages can produce sulfide melts during medium and high-grade metamorphism.

More recently, melting has been proposed for the Lengenbach (Pb-Zn-As-Tl-Ba) deposit in Switzerland (Hoffmann, 1994; Hoffmann and Knill, 1996; Knill, 1996), and the Challenger Au deposit in Australia (Tomkins et al., 2002). Lengenbach was overprinted by upper greenschist to amphibolite-facies metamorphism (T>500°C), during which As, Sb, Tl and other minor elements were released from minerals such as pyrite to form a sulfide melt that was in equilibrium with pyrite, barite, and a hydrothermal phase. Fractional crystallization of this melt-hydrothermal system led to

the formation of massive-textured sulfides from the melt, and idiomorphic sulfides from the aqueous fluid. The Challenger deposit was overprinted by granulite facies metamorphism, and formed both sulfide and silicate melts. In addition, experimental work on Bi-bearing native gold similar to that comprising most of the mineralization indicates that melting of this phase occurred near peak metamorphic conditions (Tomkins et al., 2002).

#### Metamorphism of alteration

Apart from the direct effects of metamorphism on ore minerals and the interactions of sulfide and silicate minerals, alteration assemblages in and around ore deposits are typically recrystallized and modified morphologically during metamorphism. Characterization of metamorphosed hydrothermal alteration is complicated by the fact that alteration minerals and mineral assemblages are commonly similar to those that form during regional metamorphism. For example, propylitic alteration, with the assemblage chlorite+epidote±carbonates±pyrite, is very similar mineralogically to that of a greenschist-facies metabasite. This type of problem is amplified if such rocks are subsequently deformed and metamorphosed under amphibolite-facies conditions, where they form an essentially bi-mineralic assemblage of amphibole+plagioclase.

Most descriptions of the metamorphism of alteration zones have focussed on anomalous mineral assemblages. For example, assemblages produced by H<sup>+</sup> metasomatism are commonly aluminosilicate-rich and typically do not occur in Barrovian pelitic rocks. Similarly, aluminosilicate-bearing assemblages in volcanic

rocks have been interpreted to reflect pre-metamorphic alteration (Schreyer, 1982; Tanner and Martin, 1993).

Advanced argillic alteration in epithermal and porphyry deposits, which results from intense H<sup>+</sup> metasomatism, is characterized by clay minerals such as kaolinite and illite. During regional metamorphism, clays recrystallize to aluminosilicates (pyrophyllite, andalusite, kyanite, sillimanite) and muscovite (Hemley et al., 1980), which are also common in metasedimentary rocks.

Metamorphosed intermediate argillic alteration has been interpreted to produce biotite + aluminosilicates (e.g., Stanton, 1989; Penczak and Mason, 1999). These authors suggested that biotite partially alters to kaolinite during intermediate argillic alteration, and that the remnant biotite recrystallizes to biotite, whereas the clay minerals form aluminosilicates (spatially associated with the biotite).

In some deposits, such as volcanogenic massive sulfide deposits, the seafloor origin, mineral zonation and alteration assemblages are well-established, and their metamorphosed equivalents can be linked to precursor lithologies. For example, metamorphosed Kuroko-type ores that underwent greenschist facies conditions can be shown to have chlorite-muscovite and chlorite-talc±biotite assemblages that formed from precursor minerals such as illite, montmorillionite and kaolinite (McLeod and Stanton, 1984).

Comparisons between metamorphosed and unmetamorphosed alteration zones led Stanton (1982) to argue that regionally metamorphosed bedded silicates, oxides, sulfides and carbonates are derived directly from in situ, low-T, sedimentarydiagenetic-alteration of precursor minerals, and not Barrovian prograde metamorphic

reactions. According to the 'precursor principle', regional metamorphic mineral zonation, which is normally attributed to progressively increasing T and P, is a reflection of sedimentary facies and associated diagenetic changes. Stanton (1982) argued that metamorphism is isochemical, and that product assemblages are solely functions of primary rock composition. In addition, since metamorphic diffusion occurs only over a few mm, each grain now represents the in situ growth or transformation of a pre-metamorphic material (Stanton, 1982). Although, the generalization to all Barrovian facies has not been popular, the precursor principle satisfactorily predicts many alteration sequences including those derived from chemical and exhalative sediments. For example, Wonder et al. (1988) proposed that kyanitesillimanite grade metamorphism of Fe-Mn-rich rocks, associated with massive sulfide deposits, produces garnet-bearing quartzites (coticules) and garnet-bearing Fe formations from hydrothermal sediments comprising clays, and Fe and Mn oxides (e.g., todokorite and goethite), deposited on the sea floor.

Alteration associated with mesothermal gold deposits commonly reflects metamorphic grades similar to those of the unaltered host rocks (e.g., Colvine et al., 1988; Colvine, 1989; McCuaig et al., 1993). This implies that such alteration occurred prior to metamorphism, or that the metamorphic grades reflect the depths (and thus P-T conditions) of formation (or the proximity to intrusions). The latter interpretations are especially important as they lead to the inference that lode gold deposits form over a wide range of crustal conditions. This interpretation is favored by McCuaig et al. (1993), who investigated the alteration of the Norseman Au deposits of Western Australia. These deposits occur in metabasites, which were metamorphosed from

greenschist to amphibolite facies conditions. Associated alteration assemblages vary from quartz-chlorite-calcite-biotite-plagioclase at the lowest metamorphic grades to quartz-actinolite-biotite-plagioclase-calcite at intermediate grades, and to quartz-diopside-calcite-microcline-zoisite at higher grades. However, it should be noted that the relative timing of metamorphism and mineralization/alteration for many mesothermal deposits hosted by high grade metamorphic rocks is still contentious (e.g., McCuaig et al., 1993).

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## Greenstone-hosted gold deposits

Archean volcano-sedimentary greenstone belts vary in age from ~3.5 to 2.3 Ga, and can be subdivided broadly into: (1) a lower ultramafic to mafic sequence; (2) a volcanic sequence dominated by mafic to felsic calc-alkaline units; and (3) an upper sedimentary sequence (Windley, 1984; Anhaeusser and Viljoen, 1986).

Gold is one of the principal metallic commodities of greenstone belts, and occurs in stratabound-stratiform deposits (e.g., BIF and other Fe-rich sediments), volcanogenic massive sulfides, and mesothermal lodes. The most important of these are quartz-carbonate vein-style mesothermal deposits associated with faults and shear zones (e.g., Poulsen et al., 1992). These deposits have been referred to as 'mesothermal lode gold' (Nesbitt, 1988; Nesbitt and Muehlenbach, 1989), 'metamorphogenic or metamorphic vein deposits' (Groves and Phillips, 1987; Groves et al., 1987), 'solution-remobilization ores' (Boyle, 1979; Guilbert and Park, 1986), and 'orogenic gold deposits' (e.g., Groves et al., 1998), and are hosted by rocks metamorphosed to greenschist facies, and less commonly to amphibolite facies conditions. However, rare occurrences in sub-greenschist and granulite-facies rocks have also been reported (Colvine et al., 1988; Colvine, 1989; Barnicoat et al., 1991; Groves et al., 1992; Groves, 1993; Groves et al., 2003). Typically, these deposits are also enriched in elements such as Ag, As, Sb, Hg, W, Mo, Te and B, and are usually base metal-poor (e.g., Kerrich, 1993).

Fluid inclusion data indicate that the hydrothermal fluids responsible for mesothermal mineralization are characterized by low salinity (up to 5 but generally <3 wt % NaCl equivalent), relatively high CO<sub>2</sub> contents (>4 mol %) and near-neutral pH

(e.g., Mikucki and Ridley, 1993; Heinrich et al., 2000). Gold is transported as either a bi-sulfide or chloride complex (e.g., Seward, 1973; Wood et al., 1987; Romberger, 1988; Shenberger and Barnes, 1989; Renders and Seward, 1989; Zotov and Baranova, 1989; 1995; Gammons and Williams-Jones, 1995; Benning and Seward, 1996), with bi-sulfide complexes dominating in near-neutral solutions at low to intermediate temperatures. However, hydroxy (e.g., Gammons and Williams-Jones, 1997), CO (Fyfe and Kerrich, 1984) and arsenothio (Au[AsS<sub>2</sub>]°), Au[AsS<sub>3</sub>]<sup>2-</sup>) and antimonothio (Au[Sb<sub>2</sub>S<sub>4</sub>]<sup>-</sup>) (Seward, 1984) complexes have also been proposed. In most mesothermal systems, gold is assumed to be transported as a bi-sulfide complex and is deposited as a result of boiling, interaction with cooler fluids, processes that decrease the activity of reduced S (i.e., precipitation of metal sulfides, oxidation, dilution), and decreases in pH (e.g., Hagemann and Cassidy, 2000)

Gold deposition in shear zones has been interpreted to occur in several stages, with early Au incorporated into sulfides such as pyrite, pyrrhotite and arsenopyrite, followed by precipitation of native Au into micro-fractures during continued shearing, and finally the formation of gold-bearing quartz veins in the extensional regime (Bonnemaison and Marcoux, 1990). Later stages may destroy evidence of earlier formed gold.

The setting of mesothermal deposits in complex granite-greenstone terranes without readily identifiable fluid and metal sources, has led to contradictory genetic interpretations (e.g., Kerrich, 1993). Early models often invoked syngenetic, submarine hydrothermal origins (e.g., Ridler, 1970; Hutchinson et al., 1971; Hutchinson, 1976; Fripp, 1976; Paris et al., 1985), but this is inconsistent with the fact

that most deposits are shear zone-hosted and formed either during or after regional metamorphism (e.g., Kerrich and Fyfe, 1981; Fyfe and Kerrich, 1984; Groves and Phillips, 1987). Consequently, epigenetic scenarios include a wide range of models involving metamorphic, magmatic and downward circulated meteoric fluids.

### Magmatic models

Magmatic models generally have their basis in the close spatial relationship that many mesothermal Au deposits have with igneous intrusions. For example, shear zone-hosted mineralization in the Val d'Or and Timmins areas (Quebec and Ontario) are commonly hosted by igneous rocks such as feldspar porphyry, syenite, monzonite or granodiorite (Burrows and Spooner, 1989). At the Lamaque mine, 94% of production is derived from granite-hosted veins or disseminations. Burrows and Spooner (1989) suggested that cumulate-melt separation and differentiation provide a suitable mechanism to increase Au concentrations in residual melts. Gold would then partition preferentially into a magmatically derived fluid phase.

This magmatic model was initially based on the observation that fluid characteristics in the Hollinger-McIntyre gold deposit are similar to those in the Mink Lake Au-Mo-W prospect (Wood et al., 1986; Burrows et al., 1987). The  $\delta^{18}$ O values from these two occurrences are very similar (+4 to +6 per mil), and are lower than values typical of most metamorphic fluids (+5 to +25 per mil; Wood et al., 1986). However, it should be noted that there is significant overlap between the magmatic and metamorphic fields. In addition, carbon isotope analyses of the Mink Lake, Hollinger-McIntyre and Golden Mile (Australia) deposits yielded statistically similar results, and were interpreted to reflect similar magmatic origins (Wood et al., 1986; Burrows et al., 1986). Sulfur isotope compositions in the Golden Mine district also have magmatic signatures (Cameron and Hattori, 1987). Alternative interpretations proposed for the carbon and sulfur isotopic data include equilibration of metamorphic fluids with igneous rocks (e.g., Heinrich et al., 2000), and progressive oxidation of a mesothermal fluids (Lambert et al., 1984), respectively.

# Lamprophyre, mantle degassing and granulitization models

The lamprophyre model (e.g., Rock and Groves, 1988; Rock et al., 1988, 1989) is based on the observation that Archean mesothermal Au deposits are commonly associated with calc-alkaline lamprophyres, and that these rocks generally contain more gold (average 43 ppb; Rock et al., 1989) than other igneous rocks types. This model posits that lamprophyres reflect large scale, crust-mantle events which contribute Au to metamorphism-related hydrothermal systems. Lamprophyre magmas generated by partial melting of Au-enriched metasomatized mantle are assumed to underplate the crust, and either produce granitoid-porphyry magmas, or promote devolatilization reactions and hydrothermal circulation. Gold-rich, 'lamprophyre'-derived fluids are interpreted to mix with magmatic or metamorphic fluids and then precipitate gold to form mesothermal deposits (Rock and Groves, 1988; Rock et al., 1988, 1989). However, the relationship between Au deposits and lamprophyres is questionable on both geological and geochemical grounds. For example, Au and LREE are not positively correlated, which has been interpreted to preclude mantle

metasomatism as the main process for generating Au-rich melts (Wyman and Kerrich, 1989).

Other models have also attempted, in a more general way, to relate mesothermal mineralization in Archean greenstone belts to deep-seated magmatism (e.g., mantle diapirism or crustal underplating), and subsequent granulite-facies metamorphism and crustal melting (e.g., Perring et al., 1989; Fyon et al., 1989). In these models,  $H_2O-CO_2$ -rich fluids are generated in the upper mantle, which cause anatexis in the crust. Gold is partitioned into the anatectic magmas, and subsequently released into exsolving magmatic fluids during cooling. This model is consistent with geochronological data that indicate contemporaneity between granulite-facies metamorphism, plutonism, and the emplacement of Au deposits.

#### Meteoric water models

The role of downward circulated meteoric fluids in the genesis of mesothermal mineralization was proposed originally for Phanerozoic (e.g., turbidite-hosted) deposits from the Canadian Cordillera (Nesbitt, 1988; Nesbitt and Muehlenbach, 1989), and vein-type deposits in New Zealand (Craw et al., 1987; Craw and Koons, 1989). This model posits that gold deposits, ranging from volcanic-hosted epithermal to Carlin-type and mesothermal, form a continuum. Differences in mineralization style are interpreted to reflect variations in formation depths, temperatures, and water/rock ratios involving predominantly meteoric fluids. Epithermal deposits are interpreted to form between 1 and 2 km depth, whereas mesothermal mineralization is thought to occur between 8 and 12 km depth. These interpretations were based mainly on isotopic data

(particularly  $\delta D$ ), which have sedimentary rather than metamorphic or magmatic signatures (Nesbitt, 1988; Nesbitt and Muehlenbach, 1989). However, this meteoric model has not found widespread acceptance, as the reliability of fluid inclusion (which are commonly secondary and unrelated to mineralization) and isotopic data (which are commonly inconclusive) is uncertain (e.g., Heinrich et al., 2000).

# Metamorphic models

The concept that regional metamorphic processes may be responsible for the generation of hydrothermal fluids and the mobilization of gold was first proposed by Fyfe and Henley (1973), based mainly on theoretical calculations of the amount of fluid produced by metamorphic dewatering, and estimates of the solubility of gold and silica. The 'metamorphic' (e.g., Fyfe and Henley, 1973; Henley et al., 1976; Kerrich and Fyfe, 1981; Fyfe and Kerrich, 1984) and 'metamorphic replacement' models (e.g., Groves and Phillips, 1987) hold that hydrothermal fluids derived from devolatilization reactions during regional prograde metamorphism of large source areas, are subsequently focussed into faults and shear zones. Additional fluid may be exsolved during the crystallization of igneous intrusions (e.g., Cartwright and Oliver, 2000).

Haack et al. (1984) suggested that most rocks normally contain high enough concentrations of metallic elements to generate ore deposits, and that these elements are released progressively when host minerals breakdown during prograde metamorphism. For example, Zn is commonly incorporated into staurolite, but may be liberated when staurolite reacts to form cordierite and K-feldspar. Although gold enrichment factors (deposit/background) of ~10,000 are common in mesothermal

deposits, corresponding factors for base metals vary from 0.1 to 10 (e.g., Fyfe and Kerrich, 1984). This disparity is surprising considering that base metal concentrations are much higher than gold in greenstone rocks (Haack et al., 1984). The fact that devolatilisation reactions do not remobilize significant concentrations of base metals was interpreted to be due to low water/rock ratios, and the relative abundance of S and lack of Cl (i.e., Au may be transported effectively, but base metals are left behind; Kerrich and Fryer, 1981). By contrast, Groves and Phillips (1987) suggested that gold in mesothermal deposits is derived mainly from komatilites that frequently form the lower layers of greenstone belts. This interpretation is based in part on the observation that high-Mg magmas, such as komatilites, are enriched in Au compared to tholeilites (Keays, 1984; Keays, 1987). Gold may then be precipitated by destabilization of gold bi-sulfide complexes when Fe-rich rocks interact with S-rich solutions (Phillips et al., 1984).

Currently, most researchers favor a predominantly metamorphic origin for the fluids responsible for the formation of mesothermal gold deposits (e.g., Kerrich, 1993; Goldfarb et al., 2001; McCuaig et al. 1993; Groves, 1993; Groves et al., 2003). Mesothermal deposits have similar element enrichment patterns, but are not associated with any particular type of igneous rocks; this implies that a predominantly magmatic origin is unlikely for many, and perhaps most deposits.

The observation that shear zone-hosted deposits with similar element enrichment patterns occur in sub-greenschist to granulite facies rocks (e.g., Barnicoat et al., 1991; Kerrich, 1993) has led to the 'crustal continuum model', which proposes that such mineralization is a crustal phenomenon that may occur at any depth and in rocks

with a wide range of ages (Archean to Tertiary) (Groves, 1993). However, most deposits formed in greenschist facies rocks. Since these deposits are the product of genetic processes involving orogeny, it has been proposed that they be referred to as 'orogenic gold deposits' (Groves et al., 1998). Nevertheless, not all shear zone-hosted mesothermal Au deposits are satisfactorily explained by metamorphic-orogenic models. For example, Groves et al. (2003) noted that intrusion-related deposits, although shear-hosted, are not well enough understood to be included in the current 'orogenic' model.

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# **Chapter II**

# The Role of Sulfate-Sulfide-Oxide-Silicate Equilibria in the Metamorphism of Hydrothermal Alteration at the Hemlo Gold Deposit, Ontario

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#### Abstract

The Hemlo Au (-Mo) deposit is an example of atypical, mesothermal mineralization from the Hemlo-Heron Bay greenstone belt of the Superior province of north-central Ontario. Mineralization is shear-hosted, and occurs primarily as disseminated native gold in several mineralized zones near the contact between quartzfeldspar porphyry and metasedimentary rocks. Ore occurs mainly in metasediments (i.e., pelites, greywackes, arenites, marls, mafic fragmental rocks and baritic sediments). The dominant alteration is potassic, and is characterized by a central zone of granoblastic microcline-quartz-(barite-muscovite-biotite-pyrite) rocks, surrounded by muscovite-quartz-pyrite schists. Regional, amphibolite facies metamorphism (~630°C, 5-7 kb) overprinted the ore zones and recrystallized the alteration assemblages. Unaltered sedimentary wallrocks contain the assemblages biotite-garnetstaurolite-kyanite/sillimanite (metapelites), and amphibole-plagioclase (mafic fragmental rocks and marly sediments). The presence of garnet and staurolite in unaltered metasediments, but not in the ore zones is consistent with phase equilibria which indicate that only Mg-rich silicates can co-exist with pyrite (the main sulfide in the ore zones), and that Mg-rich endmembers of garnet and staurolite are only stable at temperatures and pressures considerably higher than those of peak metamorphism. The ubiquity of muscovite + K-feldspar and lack of aluminosilicate minerals in ore zone rocks is consistent with the fact that K-feldspar is only stable at a pH above ~5, whereas aluminosilicates are unstable at a pH above ~3.5 for temperatures and pressures corresponding to those of peak metamorphism (~630°C, 5-7 kb). In altered and mineralized mafic fragmental rocks, biotite replaced amphibole, which indicates that amphibole was present prior to alteration, and that mineralization occurred at P-T conditions equivalent to those of the greenschist facies (400-500°C, 3-5 kb). Prior to mineralization/alteration, these rocks contained the assemblage actinolite + chlorite + albite + zoisite + quartz  $\pm$  carbonate  $\pm$  titanite, which was subsequently altered and metamorphosed to form biotite + muscovite + K-feldspar + plagioclase + quartz + pyrite  $\pm$  rutile.

Wallrock metasedimentary rocks are overprinted locally by marginal sulfidation and weak potassic alteration halos, and are characterized by alteration of ilmenite to rutile and pyrrhotite to pyrite proximal to the deposit. As alteration became more intense, Mg-concentrations in biotite, Zn concentrations in staurolite,  $X_{\text{pyrope}}$ ,  $X_{\text{spessartine}}$ and the proportion of muscovite all increased, and K-feldspar eventually formed adjacent to the deposit. Similarly, metasedimentary rocks adjacent to the ore zones and within the weak sulfidation halo formed early kyanite (~400°C), which was preserved through peak metamorphism by high log/S<sub>2</sub> conditions that inhibited the formation of Fe-silicates such as staurolite. The influence of sulfidation on ferromagnesian metamorphic index minerals, and the pH buffering potential of metamorphosed alteration assemblages indicate that all phases in the ore zones participated directly or indirectly in metamorphic reactions; the evolution of such rocks therefore differs significantly from those of normal metasediments. Recognition of the effects of sulfidation on metamorphosed alteration zones has significant implications for the evaluation of timing relationships and depositional models of ore zones in amphibolitegrade rocks. The disappearance of metamorphic index minerals, modification of mineral assemblages and mineralogical changes in sulfides and oxides are recognizable

on an outcrop scale at Hemlo and serve as important vectors to economic mineralization.

#### Introduction

Hydrothermal ore deposits that have undergone high grade metamorphism often present challenging mineral exploration targets as their depositional histories are frequently masked by metamorphic overprints. Recrystallized ore and alteration zones contain minerals such as muscovite, biotite, kyanite, chlorite, epidote that are also products of prograde metamorphism, ore metals are frequently remobilized, and any direct evidence of mineralizing fluids (e.g., fluid inclusions) is commonly destroyed. The Hemlo gold deposit, located in north-central Ontario (Fig. 2-1), is an example of a deposit that has suffered the masking effects of high grade metamorphism.

Despite its location adjacent to the Trans-Canada highway and a major railway line, the Hemlo gold deposit was discovered only in 1982 after years of exploration in the area. The deposit is now one of Canada's largest gold producers, and is exploited by the David Bell, Golden Giant and Williams mines. The mineralization has an average grade of  $\sim$ 8.0 g/t Au, and occurs in several zones, the most important of which is the Main ore zone, which is 3-45 m wide, and extends over a length of more than 3.7 km and to a depth of at least 1500 m (Muir, 2002).

A number of different genetic models have been proposed for Hemlo, several of which have been subsequently shown to be inconsistent with geological or geochemical features of the deposit. Early models included those of epithermal hot spring (Goldie, 1985), and exhalative seafloor mineralization (Valliant and Bradbrook,

Fig. 2-1. Simplified geological map of the Heron Bay-Hemlo greenstone belt, showing the location of the Hemlo gold mines (square in box localizing Figure 2) and major intrusions (modified from Muir, 1997).

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Fig. 2-1.

1986). However, these models failed to account for features such as extensive potassic alteration, strong enrichment of the ores in Mo and V, and discordant relationships between ore zones and the host lithologies, and thus do not provide reasonable explanations for the origin of the deposit. A skarn model (Pan and Fleet, 1992) was proposed to account for local calc-silicate alteration, and was later modified to a latestage replacement model (Pan and Fleet, 1995) that encompasses elements of porphyry, shear and skarn models. However, the dominant alteration at Hemlo is potassic, and is overprinted only locally by minor late-stage, calc-silicate alteration. Since the ore zones are extensively recrystallized and were subjected to ductile deformation, the bulk of mineralization cannot be considered to be post-metamorphic (Williams-Jones et al., 1998). Most commonly, proposed genetic models for Hemlo include elements of mesothermal-shear zone and porphyry models. The shear zone model is favored by many researchers (Burk et al., 1986; Hugon, 1986; Corfu and Muir, 1989; Muir, 1993, 1997) because of the strong structural control on mineralization. However, Hemlo differs from most Archean shear-related gold deposits in that the dominant alteration is potassic instead of carbonate/albitic, the style of mineralization is disseminated rather than vein-hosted, and there was significant enrichment of Mo. Porphyry-related models for Hemlo are favored (Walford et al., 1986; Kuhns, 1988, Kuhns et al., 1994; Johnston et al., 1995; Johnston, 1996) because of the association of native gold with molybdenite and potassic alteration, but there is no known porphyry-type intrusion in the immediate vicinity of the deposit. Modified porphyry-related models (Kuhns, 1988; Kuhns et al., 1994) have been used to suggest that the source for mineralizing fluids was a granodioritic, calc-alkaline intrusion located at some unknown depth

below the deposit. However, these models do not account for the lack of Cu in the deposit. The most recent paper on the subject (Muir, 2002), describes Hemlo as an "atypical, mesothermal-orogenic, disseminated-replacement-stockwork deposit", emphasizing the complex nature of the mineralization.

The metamorphic history of the deposit has been discussed by Burk et al. (1986), Burk (1987), Kuhns (1988), Kuhns et al. (1994), Muir (1993, 1997), Pan and Fleet (1993, 1995), Muir (1997), Powell et al. (1999), and Heiligmann et al. (Chapter 3), who place peak metamorphism within the amphibolite facies, but come to different conclusions about P-T-t relationships.

Considering the size and importance of the Hemlo deposit, and the number of previous studies, it is perhaps surprising that there is little agreement on the relative timing of the main mineralization and peak metamorphism. Studies that favor a pre- to syn-peak metamorphic timing for mineralization generally point out that the predominant potassic alteration, which is associated with the bulk of the mineralization, was recrystallized during peak metamorphism (e.g., Burk et al., 1986; Kuhns et al.; 1994; Michibayashi, 1995; Muir, 1997, 2002; Powell et al., 1999; Williams-Jones et al., 1998; Bodycomb et al., 2000; and Lin, 2001). By contrast, the association of gold with calc-silicate alteration or low temperature sulfides with thermal stabilities below that of peak metamorphism (e.g., realgar, stibnite and zinkenite), and the lack of metamorphic timing (e.g., Walford et al., 1986; Hugon, 1986; Pan and Fleet, 1992c, 1995; White and Barnett, 1990). However, late calc-silicate alteration and the presence of low temperature minerals in the ore zones can be

reconciled by invoking post-peak metamorphic remobilization of ore and ore-related minerals by hydrothermal fluids and/or a sulfide melt (Williams-Jones et al., 1998; Tomkins et al., 2003; Heiligmann et al., 2003).

The lack of metamorphic index minerals (or mineral assemblages) in the ore zones is also at apparent odds with amphibolite-facies conditions. The precursor lithologies to most ore zone rocks are metasediments similar to those found in the wallrocks (Williams-Jones et al., 1998), where garnet, staurolite and kyanite are locally abundant. Yet, these minerals are absent in the ore zones where mineralized rocks generally have the metamorphic assemblage muscovite-microcline-quartz-pyrite-rutile  $\pm$  biotite  $\pm$  barite, which is non-diagnostic of peak metamorphic conditions. The impact of metamorphism on mineralized and altered rocks and, in particular, the equilibria among silicates, oxides, sulfides and sulfates has not been investigated previously at Hemlo. In contrast to metasedimentary rocks, alteration zones often have significant proportions of sulfides and/or sulfates, and these minerals influence and/or Interaction among these minerals, or participate in metamorphic reactions. compositional changes such as the addition of S during mineralization, or K during potassic alteration can be modeled thermodynamically and used to predict the evolution of hydrothermally altered rocks during metamorphism. This can explain apparently contradictory features such as the lack of most metamorphic index minerals in Hemlo ore zones, and may help identify metamorphosed alteration zones around Hemlo-type deposits.

## **Geological Setting**

#### **Regional Geology**

The Hemlo gold deposit is hosted by Archean metasedimentary and metavolcanic rocks of the Hemlo-Heron Bay greenstone belt (Fig. 2-1), in the Wawa subprovince of the Superior Province (c.f. Williams et al., 1991; Muir, 1997, 2002). The deposit area is bordered by granitoid intrusions to the south (the Pukaskwa Gneissic Complex), northeast (Cedar Creek Stock, Cedar Lake Pluton), northwest (Gowan Lake Pluton) and southwest (Gowan Lake Pluton). Tholeiitic basalts flank the Pukaskwa Complex to the north, and the Gowan Lake pluton to the south, and form several E-W- and SW-NE-trending segments near the center of the greenstone belt (Muir, 1997). Clastic metasedimentary (mainly composed of meta-greywackes, meta-arenites, marly metasediments, metapelites) and intermediate to felsic metavolcanic rocks occur throughout the belt, but are especially abundant towards the center. Several stratiform barite lenses occur within clastic metasedimentary rocks 15-35 km from Hemlo (Patterson, 1984; Kuhns et al., 1986).

The metamorphic grade increases from west to east, as well as adjacent to granitoid intrusions, and conditions reached sillimanite grade east of the Heron Bay Pluton (Jackson, 1998). In the vicinity of the Hemlo deposit, metapelitic sediments contain biotite-garnet-staurolite-sillimanite, whereas metabasites and marly metasediments contain hornblende and plagioclase; these assemblages indicate attainment of amphibolite-facies metamorphic conditions.

The Hemlo deposit area has a complex deformational history, and not surprisingly there is some disagreement on the number or characteristics of

deformational episodes (Burk, 1987; Kuhns et al., 1994; Michibayashi, 1995; Muir, 1997, 2002; Lin, 2001). The most comprehensive studies to date described four to six deformational episodes and concluded that peak regional metamorphism occurred during or after the second major deformational event, and mineralization took place prior to peak metamorphism (Muir, 1997, 2002; Lin, 2001; Table 2-1). Although all studies agree that the second phase of deformation folded ore zone rocks, descriptions of this and subsequent deformation phases are difficult to correlate among studies (cf. Muir, 2002). For example, Kuhns et al. (1994) identified only three deformational episodes at the Golden Giant mine, and their description of structures, e.g. amplitudes of folds, differ from those of Muir (1997, 2002) or Lin (2001). The Main and Lower ore zones are hosted by the Lake Superior shear zone and the Moose Lake fault zone, respectively. In addition, a major structural break, the Hemlo fault zone, is located less then 250 m southwest of the Lower ore zone, and is interpreted to separate the Hemlo Black River and Heron Bay lithotectonic assemblages (Williams et al., 1991; Muir, 1997).

### Deposit-scale geology

Gold mineralization at Hemlo occurs primarily in two lithologically similar horizons (Main and Lower ore zones), at or near contacts between tuffaceous to massive quartz-feldspar porphyry and surrounding clastic metasedimentary rocks (Fig. 2-2). Both ore zones generally coincide with massive barite or barite-rich sedimentary rocks. The Main ore zone is locally separated from hangingwall clastic metasediments

Table 2-1. Summary of structural constraints.

	D1	D2	D3	D4	Comment
Burk (1987)	Early deformation: broadly N-S directed compression which coincided with amphibolite facies metamorphism	Late deformation: right-lateral shearing; formation of Z-type parasitic folds			Syn-peak metamorphic timing of gold mineralization
Kuhns et al. (1994)	Pre-peak metamorphic isoclinal folding	Development of large-scale (syn- peak metamorphic) isoclinal folding and post-peak ductile-brittle shearing and faulting. Development of penetrative foliation	Late brittle faulting		Pre-peak metamorphic timing of gold mineralization
Lin (2001)	Early folding	Sinistral transpression, development of camp scale folds and S2 foliation	Oblique detral shearing, development of crenulation cleavage	Development of kink bands	Pre-peak metamorphic timing of gold mineralization (mineralization before or early D2; peak metamorphism during or post-D2)
Muir (1997, 2002)	Speculatively interpreted as early low-angle thrusting; small scale, isolated (remnant?) intrafolial isoclines (F1)	Regional folding of the greenstone belt into small- to large scale, S- shaped folds (F2); a variety of styles of schistosity and cleavage (S2) and linear features (L2).	Z-shaped folds, ductile dextral shear, development of locally penetrative schistosities	Dextral and sinistral kink folds	Pre-peak metamorphic timing of gold mineralization

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Note that deformational episodes described in different studies are difficult to correlate. Studies by Muir (1997, 2002) and Lin (2001) also describe or infer additional episodes of brittle faulting

Fig. 2-2.

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Geological map of the Hemlo area (modified from Muir, 1997), showing the location of mines and distribution of mineralization (black). Note that the Lake Superior shear zone (LSSZ) and Moose Lake fault zone (MLFZ) coincide with the Main and Lower ore zones, respectively.





by a mafic fragmental unit, which is partially altered and mineralized and does not occur in footwall rocks.

The deposit is neither stratiform nor stratabound (e.g., Kuhns et al., 1986; Kuhns, 1988; Walford et al., 1986) but paraconcordant (Muir, 1997, 2002). The Main and Lower ore zones are structurally-hosted and interpreted to represent the limbs of a proto-sheath fold (Lin, 2001), which implies that metasedimentary rocks on either side of the ore zones are compositionally similar, a conclusion that is supported by the geochemical work of Bodycomb et al. (2000).

Hangingwall and footwall metasediments consist generally of interlayered, foliated and/or compositionally banded, fine- to medium-grained clastic rocks. The dominant lithologies are quartz-biotite-feldspar schists, porphyroblastic (garnet, staurolite, aluminosilicate) quartz-mica-feldspar schists, and banded calc-silicate biotite schists (Fig. 2-2).

Lithological units: Quartz-biotite-feldspar schists are interpreted to be metamorphosed greywackes, siltstones and mudstones (Kuhns, 1988). Less abundant minerals in these rocks include muscovite, garnet, and hornblende, minor pyrrhotite and magnetite, and trace tourmaline, titanite, apatite and zircon. However, compositional layering in these rocks gave rise to almandine-rich and muscovite-rich schists. Partially altered quartz-biotite-feldspar schists also contain pyrite and rutile. Less common metamorphic minerals include staurolite, sillimanite and andalusite.

Porphyroblastic rocks having a matrix of quartz, biotite and muscovite, with minor plagioclase, are interpreted to be metamorphosed pelitic sediments.

Porphyroblasts are typically poikiloblastic, and include staurolite, kyanite and garnet. Sillimanite occurs as fibrolite and commonly replaces kyanite and biotite. Less abundant minerals include pyrrhotite, tourmaline, magnetite, apatite, zircon, titanite, and arsenopyrite. Microcline, pyrite and rutile occur adjacent to the ore zone in altered rocks. Biotite locally defines a crenulation cleavage, and is commonly altered to chlorite and locally overgrown by fibrolitic sillimanite. Chlorite is commonly oriented obliquely to the foliation and is interpreted to represent late-stage alteration (Fig. 2-3), whereas the mode of occurrence of sillimanite suggests that it originated by replacement during peak metamorphic conditions. Porphyroblasts of garnet and staurolite are locally resorbed and rotated; garnet also occurs as inclusions in staurolite. Kyanite occurs both as large idioblastic blades that are locally replaced by fibrolite, and as small resorbed (xenoblastic) crystals parallel to the main foliation.

Calc-silicate rocks consist of dark green, granoblastic lenses or layers in biotitic schists, containing hornblende, quartz, biotite, actinolite-tremolite, cummingtonite, plagioclase and garnet. Minor phases include calcite, pyrrhotite, muscovite, diopside and scapolite, and trace minerals consist of apatite, zircon, tourmaline and magnetite. Pan (1990) and Pan and Fleet (1992) suggested that these rocks are skarns (products of Ca-metasomatism), which began forming during peak regional metamorphism and underwent subsequent sulfidation and gold deposition. However, the hornblende-rich mineral assemblages and the occurrence of thick calc-silicate layers interbedded with other clastic rocks suggest that these rocks are metamorphosed marly sediments. This is supported by the observation that they contain the same penetrative foliation as

Fig. 2-3.

Photomicrograph of transmitted light showing a variety of textures. (A) Recrystallized potassic alteration in the ore zones. The triple junctions suggest recrystallization of these rocks during peak metamorphism. (B) Chlorite obliquely overgrown on biotite, quartz and K-feldspar. Note that the foliation of the rocks is defined by biotite and that chlorite formed after deformation. (C) Biotitic alteration (bottom left) of mafic fragmental rocks (top right); biotite (brown) replaced amphibole (green). (D) Staurolite after kyanite in transitional metapelites. Early kyanite formation occurs in 'high-Al' metapelites, but not in pelites with Barrovian assemblages.



Fig. 2-3.

surrounding metasedimentary rocks and their mineral assemblage is consistent with amphibolite-facies metamorphism.

A relatively homogenous biotite schist is restricted to the eastern part of the deposit area between, but not adjacent to, the Main and Lower ore zones. The biotite schist is a fine- to medium-grained, massive to poorly layered, quartz-biotite-plagioclase-bearing rock with rare calc-silicate pods and garnetiferous layers, and is interpreted as a metamorphosed greywacke. Johnston (1996) proposed that this unit is a dioritic intrusion, but the schist is typically capped by thin layers containing magnetite, locally exhibits sedimentary textures, and lacks evidence of an intrusive origin.

Felsic igneous (quartz-feldspar phyric) rocks occur between the hangingwall and footwall metasediments. The porphyry is a medium-grained, granoblastic, variably foliated, and weakly-layered quartz-muscovite-microcline-plagioclase schist with traces of zircon, apatite and titanite. Altered segments of this unit adjacent to the ore zones contain minor vanadiferous muscovite, biotite, tourmaline and pyrite. Although tectonic overprinting generally obscures original contacts and primary textural relationships, several lines of evidence support a predominantly volcanic origin. These include occasional interlayering with biotitic laminae (i.e., sedimentary layers containing a mafic component) that increase in frequency toward contacts with metasedimentary and mafic fragmental rocks, and the presence of lapilli fragments and primary layering in the western extension of the deposit (cf. Muir, 1997). Some of the more massive and less schistose rocks are more evolved petrochemically than the rest

of the unit, and may be subvolcanic intrusives. Johnston (1996) suggested that the quartz-feldspar porphyry unit is an intrusive complex ("Moose Lake Porphyry Complex"), and that pink/red- coloured porphyry intruded older beige/grey- coloured equivalents. Much of the pink/red coloration is due to fracture-controlled potassic alteration (K-feldspar-epidote±chlorite), which was probably associated with postporphyry intrusion of the Cedar Creek Stock.

Mafic fragmental rocks comprise a heterogeneous lithology in the hangingwall of the deposit, that consists of quartz-biotite-feldspar-amphibole schist, with minor or trace amounts of garnet, calcite, epidote, pyrrhotite and magnetite. Mafic schists are locally overprinted by mineralization, and occasionally, fragmental textures are preserved within the ore. However, these fragmental ore zone rocks are highly altered and contain very small proportions of mafic minerals. Mineralized rocks within the mafic fragmental unit are biotitic schists and contain locally abundant microcline, pyrite, vanadiferous micas and muscovite. Burk (1987) suggested that the mafic fragmental unit is a mylonitized conglomerate; Kuhns et al. (1986), Kuhns et al. (1994), and Valliant and Bradbrook (1986) interpreted it to be a mafic volcaniclastic horizon; Johnston and Smyk (1992) and Johnston (1996) proposed that it is a biotitized hydrothermal breccia that formed in the quartz-feldspar porphyry; and Lin (2001) suggested it is a biotitized felsic fragmental unit.

Ore zones: Ore zone rocks occur in several mineralized horizons extending over 3.7 km in strike length and more than 1.5 km down-dip (Muir, 2002). The Main zone is essentially continuous through the deposit, and comprises one major and several subordinate tabular horizons located at or proximal to the contact between hangingwall metasediments, the massive barite unit, and quartz-feldspar porphyry or mafic fragmental rocks. The Lower zone is more discontinuous, and occurs within footwall metasediments (to the east), quartz-feldspar porphyry (center), or at the contact between these two units (center and west). This lower horizon is known as the "Lower Ore Zone" at the Golden Giant mine, the "C-zone" at the David Bell mine and is subeconomic at the Williams mine. Ore zone rocks are the altered and mineralized equivalents of metasedimentary, mafic fragmental, and to a lesser extent the quartzfeldspar porphyry rocks described above. They also include barite-rich rocks (located between the wallrock metasediments and the quartz-feldspar unit) which have been interpreted to be sedimentary (Cameron and Hattori, 1985; Valliant and Bradbrook, 1986; Burk, 1987; Kuhns, 1988), or hydrothermal in origin (Harris, 1989; Johnston, 1996). Our field, petrographic and geochemical observations support a sedimentary origin, in which baritic ore is the product of an altered, mineralized and metamorphosed chemical sediment interbedded with clastic and volcaniclastic material. Barite-rich rocks are characterized by recrystallized, fine-grained, granoblastic barite that forms strongly deformed layers, and breccias that contain feldspathic, siliceous and muscovitic ore fragments.

Four main subunits (feldspathic, muscovitic, baritic, biotitic) dominate the ore zone rocks (Williams-Jones et al., 1998). Feldspathic ore generally comprises finegrained, granoblastic rocks composed of Ba-microcline, quartz, pyrite and Ba-Vmuscovite, with minor amounts of barite, plagioclase, vanadiferous muscovite, and biotite, and trace amounts of calcite, titanite and tourmaline. This ore type typically

exhibits significant textural and compositional heterogeneity, including mica- and quartz-rich layers, and variable pyrite concentrations. Muscovitic ore comprises recrystallized, granoblastic quartz-muscovite-Ba-microcline schists, with locally abundant pyrite, minor amounts of barite and biotite, and trace amounts of tourmaline, calcite, zircon, titanite and apatite. Barite-rich ore consists of massive to semi-massive barite with interlayers or fragments of feldspathic and/or muscovitic material and contains quartz, barite, Ba-microcline and pyrite, lesser Ba-V-muscovite, plagioclase, and Ba-V-biotite, and traces of calcite, chlorite and titanite. Finally, biotitic ore, which occurs where mineralization overprints the mafic fragmental unit, is dominated by quartz, Ba-microcline and Ba-V-biotite, and contains subordinate barite, pyrite, Ba-Vmuscovite and plagioclase. Ore mineral assemblages are complex, and include Agand Hg-bearing native gold, pyrite, molybdenite, stibnite, realgar, sphalerite, and zinkenite.

Ore zone rocks contain evidence of a single major mineralizing event, and two remobilization events (Williams-Jones et al., 1998). The first and most important mineralizing event formed the deposit prior to peak metamorphism by introducing gold and molybdenite, with associated potassic alteration. This mineralization was succeeded near to peak- or post-peak metamorphism by large-scale sulfide melting and remobilization of ore metals including gold into low pressure dilational zones (Heiligmann et al., 2003). Post-peak metamorphic calc-silicate-related alteration locally remobilized gold in some parts of the deposit.

#### **Metamorphism**

Many aspects of the metamorphic history of the Hemlo deposit area remain controversial. Among these are the P-T conditions of peak metamorphism, particularly the pressure estimates, the possibility of multiple prograde metamorphic events, the relative timing of metamorphism with respect to mineralization, and the importance of retrograde metamorphism.

There is general agreement that peak metamorphic conditions reached those of the amphibolite facies. However, estimates of temperature and pressure vary between 500 and 650 °C and 4 to 8 kb, respectively (Kuhns, 1988; Kuhns et al., 1994; Burk, 1986; Powell et al., 1999; Pan and Fleet, 1993; Heiligmann et al., Chapter 3; Table 2-2, Fig. 2-4). Corresponding peak metamorphic mineral assemblages in metapelites and metabasites are biotite-garnet-staurolite-kyanite/sillimanite and hornblendeplagioclase, respectively.

With the exception of Pan and Fleet (1993), the above studies envisage a single metamorphic event comprising prograde and retrograde stages or suggest this as a possibility. Evidence for the retrograde stage includes reversely-zoned garnet, actinolitic/tremolitic rims on hornblende, chlorite and epidote overprinting the peak metamorphic fabric, and sillimanite overgrowths on mica. Pan and Fleet (1993) interpreted the retrograde stage to represent a second prograde episode ( $M_2$ ) based on (1) a P-T path derived from a single zoned garnet porphyroblast with mineral inclusions, and (2) the presence of andalusite, sillimanite and kyanite. They considered the presence of andalusite and sillimanite to indicate Buchan zone metamorphism (low P, defined by the index minerals staurolite, cordierite, andalusite and sillimanite), and

Study	Metamorphic events	<b>۲</b> (°C)	P kb	Comment	
Burk et al. (1986)	M1 M2	585 585	7 - 8 5	Both metamorphic events might be part of the same P-T loop	
Pan and Fleet (1993)	M1 M2	500 550-650	6 - 6.5 4 - 5	2 prograde metamorphic episodes	
Kuhns et al. (1994)	M1 M2	500-600 300-400	4 - 6.5 1 - 3	Both metamorphic events might be part of the same P-T loop	
Powell et al. (1999)	M1	600-650 600	6 - 7 4 - 5	Single metamorphic event with suggested prograde and retrograde paths	

Table 2-2. Results from previous metamorphic studies at Hemlo.

Fig. 2-4.

P-T path and relative timing of mineralization and remobilization events. The (dashed) arrow shows the path of crystallization of a Sb-As-S-dominated melt generated during peak metamorphism. An initial, rapid pressure increase is suggested by the relatively short interval between sedimentation and peak metamorphism (~10 Ma) and drawn out cooling over ~80 Ma (modified from Heiligmann et al., Chapter 3). (als – aluminosilicate, bt – biotite, chl – chlorite, kfs – K-feldspar, L – liquid, pl – plagioclase, st – staurolite, qtz – quartz, V – vapor).



Fig. 2-4.

concluded that kyanite (the high-P  $Al_2SiO_5$  polymorph) is a metastable remnant from a previous metamorphic event (M<sub>1</sub>). However, the presence of all three aluminosilicate polymorphs can also be explained by retrograde metamorphism (cf. Kuhns, 1988).

In the most extensive study to date, Heiligmann et al. (Chapter 3) applied a variety of geothermobarometers to metapelites and metabasites from the immediate deposit area and regional samples (1-3 km from the deposit), and estimated the peak metamorphic conditions as ~630°C and 5-6 kb (Table 2-2). They concluded that there was only one regional metamorphic event and that peak conditions were attained rapidly, whereas the retrograde cooling phase was protracted (>80 Ma) and coincided with at least 2 hydrothermal episodes, which remobilized gold and several ore minerals.

*Timing of mineralization*: Most studies discussing timing relationships at Hemlo, have concluded that mineralization occurred pre- or syn-peak metamorphism (e.g., Burk et al. 1986; Kuhns et al., 1994; Williams-Jones et al., 1998; Powell et al., 1999; Lin, 2001; Muir, 1997, 2002). However, some unusual features, notably the scarcity of metamorphic index minerals in the ore zones, the abundance of ore-related minerals such as realgar and orpiment, which are not stable at peak metamorphic conditions, and the association of gold with late-stage calc-silicate alteration have been used to argue for a post-peak metamorphic timing for mineralization (e.g., Hugon, 1986; Walford et al., 1986, Pan and Fleet, 1991, 1995). Nevertheless, these observations are also consistent with a pre-peak metamorphic timing for mineralization. For example, the presence of low-temperature, ore-related minerals

such as realgar and orpiment, has been explained by late-stage hydrothermal remobilization (Williams-Jones et al., 1998), sequential exsolution from a complex sulfosalt (Powell and Pattison, 1997) and post-peak metamorphic crystallization from a sulfide melt (Tomkins et al., 2003; Heiligmann et al., 2003). Moreover, most gold at Hemlo is associated with potassic alteration, whereas mineralized calc-silicate alteration zones are volumetrically minor and have been interpreted as being the product of a late-stage hydrothermal remobilization event (Williams-Jones et al., 1998). The lack of metamorphic index minerals in the ore zones is a consequence of the chemical evolution of these rocks during prograde metamorphism and will be discussed in detail below.

There are several textural lines of evidence to suggest that mineralization preceded peak metamorphic conditions. The main mineralization event at Hemlo is associated with extensive, recrystallized potassic alteration that formed either microcline or muscovite in the ore zones. Recrystallization of muscovite is evident by well foliated, idioblastic grains, and recrystallization of microcline by annealing textures such as triple junctions (Burk, 1986; Kuhns, 1988; Harris, 1989; Heiligmann et al., Chapter 4). In addition, a pre-peak metamorphic timing for mineralization is also consistent with geochronological constraints (Davis and Lin, 2003) and structural observations (Lin, 2001; Muir, 1997, 2002).

#### Alteration and mineralization

The most important and pervasive alteration at Hemlo is potassic and is characterized by a central alteration zone composed dominantly of microcline-quartz(barite-muscovite-biotite-pyrite) rocks, surrounded by muscovite-quartz-pyrite schists (Burk, 1987; Kuhns, 1988; Johnston, 1996; Williams-Jones et al., 1998; Bodycomb et al., 2000). The central core of intense K-feldspathization generally coincides with higher ore grades, and is surrounded by more extensive muscovite-rich schists that extend into hangingwall and footwall rocks. Muscovitic alteration extends up to 30 m from the ore zones at the Williams mine, and up to 15 m from those at the David Bell mine (Williams-Jones et al., 1998). Weakly mineralized muscovitic schists also identify alteration along strike from ore zones. Granoblastic, foliated and folded textures in these rocks indicate that alteration occurred prior to peak metamorphism.

Mafic fragmental rocks display three main types of alteration: biotitization, muscovitization, and late stage epidotization (Kuhns, 1988, Johnston, 1996; Muir, 1997, 2002; Williams-Jones et al., 1998; Lin 2001). Petrographic studies suggest that epidote overgrows amphiboles and micas in these rocks, and is thus a late-stage overprint, not associated with the mineralization. Biotite defines the main foliation in mafic fragmental rocks and replaces amphibole, whereas muscovite replaces biotite. Johnston (1996) concluded that the precursor of the mafic fragmental unit was a quartz-feldspar porphyry, whereas Lin (2001) interpreted it as a felsic fragmental unit with parts derived from the quartz-feldspar porphyry. In both interpretations, the mafic character is attributed to biotitic alteration. However, this is inconsistent with the widespread occurrence of amphibole and the observation that biotite replaces amphibole in altered segments of this unit (Fig. 2-3).

Post-metamorphic calc-silicate alteration is characterized by thin veins and replacement zones that frequently cross-cut tectonic fabrics in ore zones and

surrounding host rocks. These zones contain calcite, titanite, amphiboles, epidote, zoisite, diopside, pumpellyite and prehnite. As discussed above, calc-silicate assemblages (>70 % amphiboles) also occur as layers or lenses in hangingwall and footwall rocks and are penetratively deformed, parallel to lithological layering. These rocks are generally considered to represent metamorphosed marly sediments (Burk 1987; Kuhns 1988; Muir 1997; Williams-Jones et al., 1998), although Johnston (1996) interpreted them to be products of propylitic alteration of metasediments around the quartz-feldspar porphyry unit.

The ore mineralogy is complex and includes more than 50 native metal, sulfide, sulfosalt, oxide and telluride phases (Harris, 1989). Among the more common minerals are pyrite, molybdenite, stibnite, sphalerite, realgar and Pb-sulfosalts such as zinkenite and twinnite. The bulk of the gold mineralization occurs as Hg- and Ag-bearing native gold, and is closely associated with molybdenite and potassic alteration throughout the deposit (Williams-Jones et al., 1998; Bodycomb et al., 2000). Petrographic and geochemical studies by Williams-Jones et al. (1998) and Bodycomb et al. (2000) suggest that this gold-molybdenite event (Au-Mo-K event) also involved deposition of Sb, As, Hg, Pb, Zn, V, W and Tl-bearing minerals. Part of this primary ore assemblage is interpreted to have melted during peak metamorphic temperatures, and was locally remobilized into dilational zones also occupied by quartz veins (Tomkins et al., 2003; Heiligmann et al., 2003). Upon cooling, minerals such as stibnite, zinkenite, realgar, aurostibite and native gold crystallized progressively from the melt. Gold was also remobilized into calc-silicate veins by late-stage hydrothermal alteration, but this event is volumetrically minor (Williams-Jones et al., 1998).

#### Sulfide-Sulfate-Oxide-Silicate Equilibria

#### Lithogeochemical and mineral compositions

As primary mineralization occurred prior to peak metamorphism, altered and mineralized rocks evolved differently from their precursor lithologies. In unaltered sedimentary rocks, prograde metamorphic reactions occur primarily between silicates and to a lesser extent among silicates, oxides and sulfides. Variations in the mineral assemblages as a function of temperature and pressure are generally well understood and form the basis of numerous geothermobarometers. In altered and mineralized rocks, unusual mineral assemblages are produced as some elements become unusually enriched or depleted, and sulfide minerals become volumetrically important. For example, if there was addition of K to ore zone rocks, this would lead to the formation of muscovite and K-feldspar but could interfere with the formation of kyanite during prograde metamorphism; elements such as Fe that are usually partitioned among silicates and/or oxides might go into sulfide minerals. At Hemlo, an additional consideration is that mineralized rocks frequently contain appreciable concentrations of barite, which constitutes a potential source of sulfur.

Mass change calculations by Bodycomb et al. (2000) indicate that mineralization at Hemlo is hosted predominantly by altered metasedimentary rocks similar to the metamorphosed pelites, greywackes and marly mudstones that comprise the hangingwall and footwall metasediments. In these rocks, Ca, Mg and Na are depleted, whereas S, Si, Fe and especially K are enriched compared to protolith compositions (Bodycomb et al., 2000). Mineralization is also hosted by the baritic unit, and locally by mafic fragmental rocks.

A comparison of bulk rock and mineral composition data from a cross-section of the Main ore zone at Golden Giant suggests that alteration and mineralization affected the composition and distribution of minerals such as barite and biotite (Fig. 2-5). Gold mineralization is associated with the occurrence of barite, but the correlation coefficient for Au and Ba in all ore zone rocks is only 0.11 (Williams-Jones et al., 1998). This indicates that high Ba concentrations are not necessarily associated with high gold concentrations, and that ore zone rocks contain variable amounts of barite. Although Fe is also slightly enriched in ore zone rocks, Fe concentrations in biotite decrease as the bulk gold grade increases. This trend is also reflected by decreasing Fe/Mg ratios in biotite (Fig. 2-5), and suggests that, although Mg is depleted in the ore zones, Mg is partitioned preferentially into biotite. Furthermore, biotite contains significant Ba, which indicates that some barite dissolved and that Ba was partitioned into biotite (Fig. 2-5). Since biotite is the only ferromagnesian silicate of consequence in ore zone rocks, and pyrite is volumetrically the only important Fe-bearing sulfide, most Fe in the ore zones is hosted by pyrite. This interpretation is supported by a correlation factor of 0.72 for S and Fe in ore zone rocks (Williams-Jones et al., 1998).

Iron depletion in ferromagnesian silicates coexisting with sulfides and oxides has been investigated both experimentally and in field studies, and is thought to be a product of the buffering effect of sulfide-oxide assemblages (i.e., Kullerud and Yoder, 1963; 1964; Froese, 1969, 1977; Tso et al., 1979; Peterson, 1984; Nesbitt, 1986a,b; Spry, 2000 and references therein). At Hemlo,  $fS_2$  was buffered not only by the

Fig. 2-5.

Cross-section through the Main ore zone (grey; drill hole 440NQ-34), comparing bulk rock and biotite compositions (wt% oxide). In the ore zone, Fe concentrations and the Fe/Mg ratio in biotite decrease, and whole rock Fe concentrations increase.



Fig. 2-5.

sulfide-oxide assemblage, but also by sulfate in the form of barite. The high Ba concentration of alteration-related K-feldspar and mica indicates that barium was mobilized by sulfate dissolution, and was redistributed by hydrothermal fluids that interacted with silicate minerals.

In many metamorphosed ore deposits, high Mg/(Mg+Fe) ratios are observed in ferromagnesian minerals such as garnet, staurolite, cordierite and chlorite (e.g., Nesbitt, 1986b). However, these minerals are either absent or extremely rare in the prograde assemblage of the Hemlo ore zone rocks, except near the margins of the mafic fragmental unit. This suggests that there was insufficient Fe available for the formation of almandine and other Fe-silicates.

At Hemlo, a similar trend is observed for oxides, with ilmenite and magnetite present in country rocks or at the margin of the mafic fragmental unit but absent in mineralized rocks. Furthermore, minerals such as sphalerite and tourmaline, that may contain appreciable Fe, are generally Fe-poor in the ore zone. Sphalerite generally contains <<1 wt% Fe (Harris, 1989), and the Fe/(Fe+Mg) ratio of tourmaline is <0.05 compared to >0.3 outside the ore zone (Fig. 2-6).

#### fS<sub>2</sub>-fO<sub>2</sub> modeling

The ubiquitous occurrence of pyrite in the ore zones contrasts the conspicuous lack of Fe-oxides, metamorphic index minerals such as garnet and staurolite, and the low Fe/Mg ratios in biotite, and indicates that sulfidation of the deposit preferentially partitioned Fe into sulfide. Sulfur activity was therefore a controlling factor in the evolution of the silicate mineral assemblage during metamorphism. Phase equilibria

Fig. 2-6.

Fe/(Fe/Mg) mole ratios of tourmaline across the Main ore zone. The inverse relationship between Fe/(Fe+Mg) and bulk Au suggests that Fe was unavailable for substitution into silicate minerals due to the high  $fS_2$  that prevailed during metamorphism (see text for details).


Fig. 2-6.

involving sulfidation-oxidation reactions among silicates, oxides and sulfides are normally illustrated using  $fS_2$ - $fO_2$  diagrams (e.g., Froese, 1971; Zaleski et al., 1991; Table 2-3). In general, the magnesian end-members for most ferromagnesian silicates are stable in the pyrite stability field, whereas in the pyrrhotite stability field, ferroan end-members are stable (Figs. 2-7 and 2-8). For biotite, only near end-member annite is stable with pyrrhotite, and phlogopitic compositions are predominant in the pyrite stability field. This is consistent with very low Fe/(Fe+Mg) ratios for ore zone biotite, and the presence of pyrite as the dominant ore zone sulfide mineral.

An important effect of the restriction of Fe-Mg silicate minerals in the pyrite stability field to their Mg-endmembers is that it precludes formation of metamorphic index minerals like garnet and staurolite which are not stable under amphibolite-facies conditions. For example, garnet with  $X_{Fe}$ =Fe/(Fe+Mg)=0.5 is stable only at pressures of 18 kb at the temperature of peak metamorphism (~630°C), and this pressure increases with decreasing  $X_{Fe}$  (Spear, 1993). At the high  $fS_2$  of the ore zone and with preferential partitioning of Fe into pyrite,  $X_{Fe}$  of garnet is likely to be much lower. Assuming Fe-Mg partitioning between garnet and biotite similar to that in unaltered metapelites (where Fe/(Fe+Mg) is much higher),  $X_{Fe}$  in garnet would have to be as low as 0.2 to be in equilibrium with ore zone biotite (phlogopite) (Fig. 2-8). Similarly, Mg-rich staurolite is only stable at temperatures corresponding to peak metamorphism when pressure is very high (> 12 kb; Fockenberg, 1998), and has only been reported from eclogites and sapphirine-bearing rocks. Under amphibolite-facies conditions staurolite is very iron-rich ( $X_{Mg} < 0.3$ ; Deer et al., 1992). Another reason why staurolite did not form in ore zones may be that these rocks were greatly enriched in K,

)

Reaction	400°C, 4 kb logK	600°C, 5 kb logK	
$Fe + 0.5S_2 = FeS$	8.6	5.9	
$FeS + 0.5S_2 = FeS_2$	37	11	
$3Fe + 2O_2 = Fe_3O_4$	68.4	48 0	
$3FeS + 2O_2 = Fe_3O_4 + 1.5S_2$	42.6	31 3	
$3\mathrm{FeS}_2 + 2\mathrm{O}_2 = \mathrm{Fe}_3\mathrm{O}_4 + 3\mathrm{S}_2$	31.6	27.9	
$2\text{FeS}_2 + 1.5\text{O}_2 = \text{Fe}_2\text{O}_3 + 2\text{S}_2$	25.1	21.5	
$2Fe_3O_4 + 0.5O_2 = 3Fe_2O_3$	12.1	76	
$FeTiO_3 + 0.5S_2 = TiO_2 + FeS + 0.5O_2$	-9.8	-77	
$2BaSO_4 + 4H^+ = S_2 + 2Ba^{2+} + 2H_2O + 3O_2$	-70.2	-/./	
$KFe_3AlSi_3O_{10} (OH)_2 + 1.5S_2 = KAlSi_3O_8 + 3FeS + 1.5O_2 + H_2O$	-29.4	-21.7	
$KFe_3AlSi_3O_{10} (OH)_2 + 3S_2 = KAlSi_3O_8 + 3FeS_2 + 1.5O_2 + H_2O$	-18.4	-18.2	
$3FeS + KAl_3Si_3O_{10} (OH)_2 + 3SiO_2 + 1.5O_2 = Fe_3Al_2Si_3O_{12} + KAlSi_3O_8 + 1.5S_2 + H_2O_3O_1 + KAlSi_3O_8 + 1.5S_2 + H_2O_3O_1 + KAlSi_3O_1 + KAlSi_3O_1 + KAlSi_3O_1 + KAlSi_3O_2 + 1.5O_2 = Fe_3Al_2Si_3O_{12} + KAlSi_3O_8 + 1.5S_2 + H_2O_3O_1 + KAlSi_3O_1 + KAlSi_3O_1 + KAlSi_3O_1 + KAlSi_3O_2 + 1.5O_2 = Fe_3Al_2Si_3O_{12} + KAlSi_3O_1 + KAlSi_3O_1 + KAlSi_3O_2 + 1.5O_2 = Fe_3Al_2Si_3O_{12} + KAlSi_3O_1 + KAlSi_3O_2 + 1.5O_2 = Fe_3Al_2Si_3O_{12} + KAlSi_3O_2 + 1.5O_2 + H_2O_3O_2 + KAlSi_3O_3 + 1.5S_2 + H_2O_3O_3O_3 + 1.5S_2 + H_2O_3O_3O_3O_3O_3O_3O_3O_3O_3O_3O_3O_3O_3O$	28.9	22.8	
$3FeS_2 + KAl_3Si_3O_{10} (OH)_2 + 3SiO_2 1.5O_2 = Fe_3Al_2Si_3O_{12} + KAlSi_3O_8 + 3S_2 + H_2O_3$	17.9	19.4	
$Fe_4Al_{18}Si_{7.5}O_{48}H_4 + 2S_2 + 9KAlSi_3O_8 + 7H_2O = 7.5SiO_2 + 4FeS + 9KAl_3Si_3O_{10}(OH)_2 + 2O_2$		-26.6	

• .

Table 2-3. Reactions and logK's for the  $logfO_2 - logfS_2$  diagrams.

All thermodynamic data from the SUPCRIT92 database (Shock et al., 1997), except for ilmenite, rutile, garnet and staurolite from Holland and Powell (1998). Log K's were calculated using the HCH/UNITHERM program (Shvarov, 1999; Shvarov and Bastrakov, 1999). Note that p<sub>H20</sub> = 1 for all calculations.

# Fig. 2-7.

Log/ $O_2$ -log/ $S_2$  diagram showing stability fields of annite (dash-two dots), 'ore zone' biotite (dash-dot), almandine (dotted) and wallrock garnet (dashed) at 400°C and 4 kb. The grey circle shows approximate conditions in the ore zones as indicated by the intersection of the barite saturation boundary with the line representing the breakdown of ore zone biotite to pyrite. Stability of 'ore zone' biotite is calculated with representative data from the ore zones, and pH was fixed at ~4.5 (Heiligmann et al., Chapter 4). Note that the Fe end-members generally are not stable in the pyrite stability field.



Fig. 2-7.

### Fig. 2-8.

Log/O<sub>2</sub>-log/S<sub>2</sub> diagram showing stability fields of selected sulfide, oxide and silicate minerals at 600°C and 5 kb. Annite (dash-two dots) and almandine (dotted) are not stable in the pyrite stability field. Ilmenite (grey) is stable with garnet and Fe-biotite in the pyrrhotite stability field, whereas rutile is stable over the entire field of pyrite stability. The stability field of 'ore zone' biotite was calculated with compositional data from mineralized rocks. Note that staurolite is stable in the pyrrhotite and magnetite stability fields below a  $log/S_2$  of ~9 (based on data of Holland and Powell, 1998).



Fig. 2-8.

which stabilized K-feldspar at the expense of staurolite by consuming aluminum, an effect that was further enhanced by the high Ba activity; K-feldspar in the ore zones locally has high concentrations of celsian. Finally, thermodynamic modeling, using the database of Holland and Powell (1998), indicates that whereas Fe-staurolite is stable in the pyrrhotite and magnetite stability fields at T>550°C, it is unstable in the pyrite stability field. In summary, sulfidation-oxidation buffering and high potassium activities inhibited the formation of most ferromagnesian silicates in ore zone rocks.

Field and petrographic observations indicate that rutile is ubiquitous in the ore zones, where it contains significant Sb and V, but rare in country rocks where ilmenite is the principal Ti-mineral. This is consistent with thermodynamic relationships indicating that in pyrite-bearing ore zone rocks, ilmenite is unstable (Figs. 2-7 and 2-8). It is worth noting that rutile is generally associated with Mg-rich silicates in metamorphosed ore deposits, an association that has also been noted for Mg-rich bulk compositions in metapelites (Thompson, 1972).

The occurrence of sedimentary barite and barium substitution into silicate alteration minerals in the ore zones suggest that  $fS_2$ - $fO_2$  conditions were buffered by sulfate as well as by sulfide mineralogy, a conclusion which is supported by the fact that the barite dissolution curve intersects the pyrite stability field (Fig. 2-7). This supports a hypothesis that barite dissolved in fluids associated with gold mineralization and associated alteration and was also redistributed in ore zone rocks during metamorphism.

## Activity of K<sup>+</sup> and Na<sup>+</sup>

The bulk of the gold mineralization at Hemlo is associated with potassic alteration, manifested by high-grade ores containing 40-45 % (locally up to 90 %) microcline and 1-10 % muscovite, surrounded by lower grade ores that contain 1-10 % microcline and 15-30 % (locally up to 60 %) muscovite (Williams-Jones et al., 1998). The ubiquitous presence of these minerals also had the effect that the pH in the ore zones was buffered by the reaction:

$$0.5 \text{ KAl}_3 \text{Si}_3 \text{O}_{10}(\text{OH})_2 + 3 \text{Si}_2 + \text{K}^+ = 1.5 \text{ KAl}_3 \text{O}_8 + 2\text{H}^+$$
(1)

This reaction indicates that for a specific activity of  $K^+$ , pH is fixed, and that an increase in  $aK^+$  will stabilize K-feldspar. As a consequence, the reaction between muscovite and aluminosilicates, which is also pH dependent, is not stable:

$$2KAl_{3}Si_{3}O_{10}(OH)_{2} + 2H^{+} = 3 Al_{2}SiO_{5} + 2K^{+} + 3SiO_{2} + 3H_{2}O$$
(2)

The effect of potassic alteration on aluminosilicate stability can be predicted from stability relationships among muscovite, K-feldspar, paragonite, albite and kyanite as function of  $aK^+/aH^+$  and  $aNa^+/aH^+$ . As is evident from Figure 2-9, potassically altered rocks with the equilibrium assemblage muscovite+K-feldspar, cannot contain aluminosilicates. With increasing temperature, the muscovite (and paragonite) field contracts and disappears at T>650°C. This disappearance of muscovite is generally associated with a second generation of sillimanite formation, referred to as the 'second sillimanite isograd'. However, these temperatures were not realized during peak metamorphism at Hemlo and therefore aluminosilicates are not in equilibrium with ore zone rocks.

# Fig. 2-9.

Phase relations in the system log  $a(K^+/H^+)$  versus log  $a(Na^+/H^+)$  at 500°C, 5 kb (italics/dashed) and 630°C, 5kb (black/solid), the latter approximating conditions of peak thermal metamorphism. Note that kyanite and K-feldspar cannot exist stably together under these conditions, and that the paragonite field is absent at 630°C.



Fig. 2-9.

### Mafic fragmental unit

The mafic fragmental unit has been interpreted as a mylonitized conglomerate (Burk, 1987), a mafic volcaniclastic horizon (Kuhns et al., 1986; Kuhns et al.; 1994; Valliant and Bradbrook, 1986), and a biotitized hydrothermal breccia (Johnston and Smyk, 1992; Johnston, 1996). Lin (2001) also suggested that part of this unit formed by biotitic alteration of the quartz-feldspar porphyry unit. The multiplicity of interpretations is in large part due to the heterogeneous nature of the mafic fragmental unit, and the difficulty of distinguishing among precursor minerals, later alteration minerals, and subsequent metamorphic minerals. Mafic fragmental rocks have generally higher Ti/Al ratios than adjacent metasedimentary and quartz-feldspar porphyry rocks (Williams-Jones et al., 1998). A comparison of immobile element ratios, such as Ti/Al versus Ti/Zr, clearly indicates that the quartz-feldspar porphyry is an unlikely precursor for the mafic fragmental unit (Fig. 2-10), and that there is a significant overlap between ratios for metasediments and mafic fragmental rocks. Therefore, it is likely that the mafic fragmental unit is a conglomerate with a strong mafic component. It is also probable that the alteration assemblage in this unit was modified during metamorphism. Biotite replaced amphibole (Fig. 2-3), which suggests that amphibole was present prior to alteration and implies that, during the initial stages of prograde metamorphism, mafic fragmental rocks evolved along a metamorphic path similar to that of the metabasites.

# Fig. 2-10.

~

Comparison of Ti/Al and Ti/Zr ratios in mafic fragmental, felsic volcanic and metasedimentary rocks. Note that the mafic fragmental unit and felsic porphyry rocks have distinctly different immobile element ratios, which indicates that the precursor of the former is unlikely to be a felsic volcanic/intrusion. Overlap of felsic volcanic rocks with metasediments is due to local interfingering of these lithologies.



Fig. 2-10.

In classic metabasites, the lowermost greenschist-facies assemblage is chlorite + albite + zoisite + quartz  $\pm$  carbonate  $\pm$  titanite. Actinolite (Ca<sub>2</sub>(Fe,Mg)<sub>5</sub>Si<sub>8</sub>O<sub>22</sub> (OH)<sub>2</sub>) is the first amphibole to appear with progressive heating. However, the occurrence of actinolite is not only a function of P and T but also of the Fe/Mg ratio and Pco<sub>2</sub>. High values of Pco<sub>2</sub> increase the stability of chlorite + carbonate over that of actinolite + zoisite. Actinolite forms at lower temperatures in Fe-rich rocks than in Mg-rich equivalents (Spear, 1993, p.404). In the amphibolite facies, plagioclase evolves from albite to oligoclase, and actinolite forms hornblende, while chlorite becomes increasingly Mg-rich and eventually disappears, and epidote decreases in abundance and also eventually disappears (Spear, 1993). Thus, in metabasites at amphibolitefacies conditions, the stable mineral assemblage is hornblende + Ca-plagioclase  $\pm$ quartz  $\pm$  chlorite  $\pm$  epidote. The replacement of amphibole by biotite in the mafic fragmental unit suggests that mineralization/alteration occurred at P-T conditions equivalent to at least those of the greenschist facies. This implies that prior to mineralization/alteration, these rocks contained the assemblage actinolite + chlorite + albite + zoisite + quartz  $\pm$  carbonate  $\pm$  titanite, which was subsequently altered and metamorphosed to form biotite + muscovite + K-feldspar + plagioclase + quartz + pyrite  $\pm$  pyrrhotite  $\pm$  rutile  $\pm$  ilmenite. During alteration, K and S were enriched in the ore zones, and Na and Ca were depleted (Bodycomb, 2000; Williams-Jones et al., 1998). Chemically, the effect of addition and removal of these components on these mineral assemblages can be seen from the following reactions (note that  $K_2O$ ,  $Na_2O$ and CaO are proxies for the corresponding aqueous species, since speciation is not pertinent to these reactions):

3chlorite +  $4K_2O$  + 2albite + 9quartz +  $6H_2O$  +  $3.5O_2 \Leftrightarrow$ 

$$5biotite + 3K-feldspar + 2Na_2O \tag{3}$$

chlorite + quartz + 
$$K_2O + 2S_2 \Leftrightarrow$$
 phlogopite + 2pyrite + K-spar +  $3H_2O + O_2$  (4)

$$2\text{zoisite} + \text{H}_2\text{O} + \text{K}_2\text{O} \Leftrightarrow 2\text{muscovite} + 4\text{CaO}$$
(5)

actinolite + zoisite +  $2S_2 + K_2O + CO_2 \iff$ 

biotite + calcite + pyrite + anorthite + quartz + 
$$0.5H_2O + O_2$$
 (6)

In highly altered rocks or parts of this unit that were initially less mafic due to heterogeneity, biotite decomposed further to form a final assemblage of muscovite, Kfeldspar, pyrite and quartz. Since some Fe is partitioned into sulfides (pyrite or pyrrhotite, depending on sulfur fugacity), less iron was available for silicate reactions, which in turn inhibited the formation of minerals such as garnet and staurolite. Potassium that was added during alteration also inhibited the formation of aluminosilicate minerals such as kyanite and sillimanite by stabilizing K-feldspar.

Proposals by Lin (2001) and Johnston (1996) that the precursors of the mafic fragmental unit were mainly felsic fragmental or intrusive units in which a mafic mineral (biotite) was added during alteration are inconsistent with the ubiquitous occurrence of amphibole in unaltered marly rocks, textural evidence which indicates that biotite replaced amphibole, and the higher Ti/Al ratios of the mafic fragmental rocks. In fact, the precursor to this unit could be analogous to a Temiskaming-type conglomerate (mostly felsic fragments in an intermediate to mafic matrix) which occurs locally in the vicinity of lode-gold systems in the Timmins-Val D'Or area.

### The ore zone - hangingwall transition

The most important mineralized horizon at Hemlo is the Main ore zone, which is continuous throughout the deposit, and is located between the quartz-feldspar porphyry and hangingwall metasediments (including the mafic fragmental unit) (Fig. 2-11. Quartz-feldspar porphyry rocks generally contain the silicate assemblage quartzfeldspar-muscovite, and during metamorphism these rocks generally only recrystallized but did not evolve metamorphic index minerals. The Lower ore zone, which is only present locally at the Golden Giant and David Bell mines, is more restricted in distribution, and has a less extensive alteration envelope. Therefore, our description of the evolution of the ore zone–country rock transition zone during metamorphism will focus on the contact of the Main ore zone with hangingwall metasediments (Fig. 2-11).

The precursor lithologies to the main ore zone include a number of different sedimentary rock types, several of which also occur in hangingwall rocks. These include meta-greywackes, meta-arenites, marly sediments, and metapelites, which, since the ore zone is neither stratiform nor stratabound (Muir, 1997), intersect the ore zone at an oblique angle. Due to their proximity to the ore zone, these lithologies are overprinted by the sulfidation and alteration halos, although this overprint is weaker than in the ore zone.

Regardless of their precursor composition, rocks within the alteration/sulfidation halo show common variations. Grading from the ore zone outwards, sulfide abundance decreases and pyrite is replaced by pyrrhotite. Similarly, rutile, which is a common oxide in the ore zone, is replaced by ilmenite in unaltered hangingwall rocks (Fig. 2-11, 2-12). Locally, magnetite also occurs in hangingwall

Fig. 2-11.

Stylized cross-section through the Hemlo ore zones showing the variation of mineral assemblages and differences in mineral compositions. Note that metamorphic index minerals are not present in the ore zones.  $X_{Fe}$  in biotite and staurolite were calculated as molecular proportions of Fe/(Fe+Mg);  $X_{Ba}$  and  $X_{Zn}$  in molecular proportions;  $X_{almandine}$  in molecular proportions (Fe/(Fe+Mg+Mn+Ca)). Abbreviations: amphibole (amph), anhydrite (anh), biotite (bt), feldspar (fsp), garnet (gt), ilmenite (ilm), K-feldspar (kfs), kyanite (ky), magnetite (mag), muscovite (ms), plagioclase (plag), pyrite (py), pyrrhotite (po), quartz (qtz), rutile (rt) sillimanite (sil), staurolite (st),

footwall metasediment footwall metasediment footwall metasediment footwall metasediment footwall metasediment footwall metasediment footwall metasediment footwall metasediment footwall metasediment footwall metasediment footwall metasediment footwall metasediment footwall metasediment footwall metasediment footwall metasediment footwall metasediment footwall metasediment footwall footwall metasediment footwall foo									
assemblages	footwall metasediments	lower ore zone	qtz-fsp porphyry	main ore zone	mafic fragmental unit	hangingwall metasediments			
silicates	qtz, ms, bt, gt, st ky, sil, plag	qtz, ms, bt, kfs	qtz, ms, kfs, plag	qtz, ms, bt, kfs	qtz, ms, bt, amph, plag, kfs, gt, sil?	qtz, ms, bt, gt, st ky, sil, plag			
sulfides, sulfates	py, po py, brt, anh		ру	py, brt, anh	py, locally po	ру, ро			
oxides	rt, ilm	rt	rt	rt	rt rt, ± ilm, ± mag				
X <sub>Fe</sub> in biotite	0.44	0.02 - 0.05	0.31 - 0.42	0.02 - 0.05	unaltered: 0.3-0.42 altered: 0.1	unaltered: 0.4+ altered: 0.07-0.13			
X <sub>almandine</sub> in garnet	<sub>dine</sub> in 0.6 none		none	none	none	0.59 - 0.79			
X <sub>Zn</sub> and X <sub>Fe</sub> in staurolite	$X_{zn} = 0.02$ $X_{Fe} = 0.85$	$X_{2n} = 0.02$ $X_{Fe} = 0.85$ none		none	none	$X_{Zn} = 0.06$ $X_{Fe} = 0.8+$			
X <sub>Ba</sub> in kfs	none	0.02 - 0.18	0.01 - 0.02	0.1 - 0.35	unaltered: 0.01 - 0.02 altered: 0.3	none			

Fig. 2-11.

Fig. 2-12.

Simplified cross-section showing the distribution of selected metamorphic and ore zone minerals in the Main ore zone and adjacent wallrocks. In the transition between these units metamorphic index minerals disappear and pyrite and rutile are replaced by pyrrhotite and ilmenite (line thickness corresponds roughly to relative mineral abundance).

Main ore zone feldspathic, baritic, muscovitic ore and mineralized mafic fragmental rocks	ky-bt schists	metasedimentary wallrocks metagreywackes, meta-arenites, metapelites, and metamorphosed marly sediments
Au	ija = = = +	
		pyrrhotite
rutile		
		ilmenite
		kyanite
	•	staurolite
		garnet
barite	<b></b>	
phlogopite		annite

Fig. 2-12.

rocks together with pyrrhotite and ilmenite. In some cases the full assemblage pyritepyrrhotite-rutile-ilmenite $\pm$ magnetite may be seen in a single thin section. This is consistent with thermodynamic data predicting equilibration of these minerals under similar  $fS_2-fO_2$  conditions (Fig. 2-8).

These changes are interpreted to have resulted from sulfidation of the rock by reaction:

$$FeS + FeTiO_3 + 1.5S_2 = 2FeS_2 + TiO_2 + 0.5O_2$$
 (7)

and locally by the reaction:

$$Fe_3O_4 + FeTiO_3 + 4S_2 = 4FeS_2 + TiO_2 + 2.5O_2$$
 (8)

Rutile and pyrite are generally absent outside the alteration zone, suggesting that their appearance defines the limits of the sulfidation-oxidation halo around the deposit.

In addition to these relatively common changes in sulfides and oxides, there are corresponding changes in the silicate assemblages of these rocks, which vary with the precursor lithology. Gold-bearing muscovitic schist surrounding the central, high grade, K-feldspar-rich alteration zone generally contains the assemblage quartz-muscovite-Ba-microcline, plus locally abundant pyrite, and minor amounts of barite and biotite. Where the ore zone grades outwards into marly sediments, mineralogical changes are similar to those observed in the mafic fragmental unit. Biotitic schists containing the (silicate) assemblage biotite-muscovite-feldspar-quartz±amphibole near the ore zone grade outwards into amphibole-feldspar-quartz±biotite±muscovite-bearing metasediments. This implies that near the ore zone amphibole broke down to biotite,

and locally, to muscovite. These changes can be related to the potassic alteration and sulfidation halo that extends into the hangingwall.

Meta-greywackes that contain the silicate assemblage muscovite-feldsparquartz-biotite near the ore zone evolve into unaltered rocks containing the assemblage biotite-feldspar-quartz±muscovite. Meta-arenites, composed of muscovite-quartzfeldspar at the contact of the ore zone, grade into quartz-feldspar±muscovite rocks in the hangingwall. The principal changes in the silicate mineralogy of these rocks are therefore a decrease in the proportion of muscovite, and in the case of metagreywackes, an increase in the proportion of biotite. These changes are related to progressively weaker sulfidation and potassic alteration. Since unaltered greywackes and arenites generally do not evolve other metamorphic index minerals (such as garnet and staurolite) during amphibolite-facies conditions, the alteration envelope is only recognized by changes in the proportions of minerals, rather than a change in mineral assemblage, and is therefore quite subtle.

In contrast to the preceding rock types, metapelites, which are a volumetrically important hangingwall lithology, show a clear change in their mineral assemblage, expressed by an increase in the number of metamorphic index minerals with distance from the ore zone. Muscovitic ore grades outwards into kyanite-quartz-feldspar ±muscovite±biotite schist, followed by kyanite-staurolite-biotite-quartz-feldspar±muscovite schist, until a typical amphibolite-facies metapelitic assemblage of biotite-garnet-staurolite-kyanite/sillimanite is reached. The proportion of kyanite, which may locally reach up to 40% of these rocks in the vicinity of the ore zone, decreases progressively as other metamorphic index minerals appear in these rocks.

The dominant sulfide in kyanite-rich rocks is pyrite, and pyrrhotite generally is absent, indicating that these rocks are within the sulfidation envelope.

In addition to these mineralogical changes, systematic compositional variations also occur in metapelites outward from the ore zone. The Fe/(Fe+Mg) ratio of silicate minerals (such as biotite, garnet and staurolite) increases systematically, and in the case of biotite increases from 0.02 in the ore zone to >0.4 in hangingwall rocks (Fig. 2-11). Although almandine garnet is absent from the ore zone, in the transition zone it shows a general trend of decreasing  $X_{almandine}$  and increasing  $X_{spessartine}$  component with proximity to mineralization;  $X_{almandine}$  varies from 79% to 65%, whereas  $X_{spessartine}$ increases from ~2% to 15%. Garnet near the deposit shows both normal (Mn higher in cores than rims) and reverse (Mn higher in rims than core) zonation. Staurolite near the ore zone contains up to 0.65 wt% Zn, and ~0.1 wt% Zn in more distant samples, which indicates that there was significant remobilization of Zn from the deposit (Fig. 2-11). The enrichment of Zn in staurolite in the vicinity of ore deposits is relatively common and especially pronounced near base metal occurrences (e.g., Spry, 2000).

These observations imply that the alteration and sulfidation halos around the deposit caused mineralogical and compositional changes that extend into the hangingwall rocks. These variations are especially evident in rocks that contain a more complex mineralogy such as metapelites.

### Discussion

### Origin of the kyanite-rich, hangingwall metapelites

The kyanite-rich hangingwall rocks have been interpreted as the product of either compositional layering (Burk, 1987) or metamorphism of argillic alteration (Kuhns, 1988; Kuhns et al. 1994; Kusins et al., 1991; Johnston, 1996). The latter interpretation is based on the observation that argillic alteration (intense H+ metasomatism), converts primary silicates to kaolin group clays, and these clay minerals may in turn be converted to aluminosilicates during metamorphism. In the process, elements such as K, Na, Mg, Fe and Ca are leached from the system. However, the bulk composition and the distribution of these rocks are inconsistent with an argillic alteration overprint. Bulk rock geochemical analyses of these rocks indicate that although Fe and Mg concentrations are low and that of Si is relatively high, Ca, K and Na concentrations are within the normal range of Hemlo metapelites. Advanced argillic alteration should have greatly reduced the concentrations of these elements (Table 2-4). Metapelites with low contents of Fe and Mg are also present in footwall metapelites, but these rocks contain mineral assemblages such as biotite-garnetstaurolite±kyanite. This suggests that earlier alteration did not control the metamorphic mineral assemblage in the kyanite-rich rocks. In addition, the distribution of kyaniterich rocks is mainly stratigraphically-controlled, whereas ore locally transgresses stratigraphy (Muir, 1997; Williams-Jones et al., 1998), and argillic alteration generally requires either very high water-rock ratios or low pH, which are unlikely to have occurred outside the shear-zone-hosted ore zones.

Table 2-4. Bulk rock data for Hemlo metapelites.

Rock type	Metamorphic	SiO₂	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na₂O	K₂O	TiO₂	P <sub>2</sub> O <sub>5</sub>	LOI	TOTAL
	assemblage	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%
Hemlo metapelite Hemlo metapelite Hemlo metapelite Hemlo metapelite Kyanite-rich metapelite Kyanite-rich metapelite Kyanite-rich metapelite	bt-gt-st-ky bt-gt-st-ky bt-gt-st-ky bt-st bt-ky bt-ky ky ky	64.16 60.67 64.65 65.83 74.68 74.29 65.92 79	16.02 18.06 16.76 17.9 14.12 14.5 23.02 13.46	8.57 8.43 8.02 4.96 2.32 2.73 2.57 0.93	0.18 0.13 0.15 0.05 0.06 0.02 -0.01 -0.01	1.94 3.09 1.78 1.74 0.72 1.32 0.09 0.08	3.02 1.98 2.6 1.54 3.1 2.4 1.86 1.28	2.54 2.69 1.98 2.23 1.54 1.8 1.76 1.59	0.89 2.8 1.21 2.76 1.15 0.86 1 0.85	0.78 0.69 0.8 0.68 0.32 0.36 0.53 0.34	0.16 0.2 0.18 0.17 0.11 0.2 0.05 0.1	1.67 1.09 1.28 2.1 1 0.74 1.62 0.75	99.94 99.83 99.4 99.95 99.11 99.22 98.43 98.4

LOI = lost on ignition; bt = biotite, gt = garnet, st = staurolite, ky = kyanite

However, since kyanite-rich rocks occur only near the ore zones, the question remains as to the control of their distribution. In this paper, the kyanite-rich rocks are referred to as 'high-Al' metapelites since they plot above the garnet-chlorite join near the Al apex on an AFM diagram, due to their low Fe and Mg concentrations (Fig. 2-13). High-Al pelites do not form index minerals in the same order as normal, 'low-Al' (or 'Barrovian') pelites. The progression in the former is generally chlorite  $\rightarrow$ chloritoid  $\rightarrow$  andalusite/kyanite  $\rightarrow$  staurolite  $\rightarrow$  garnet  $\rightarrow$  kyanite/sillimanite, compared to chlorite  $\rightarrow$  biotite  $\rightarrow$  garnet  $\rightarrow$  staurolite  $\rightarrow$  kyanite/sillimanite in Barrovian metapelites. The early aluminosilicate phase in high-Al metapelites usually disappears during the formation of staurolite. However, since the kyanite-rich rocks are within the sulfidation envelope and initially contained low Fe concentrations, staurolite and garnet did not form. This implies that the early aluminosilicate phase is preserved throughout the metamorphic cycle. However, in kyanite-staurolite-biotitemuscovite-quartz-feldspar-bearing schists at the edge of the sulfidation halo, staurolite frequently replaced kyanite (Fig. 2-3), consistent with mineral evolution in high-Al metapelites.

The presence of kyanite+muscovite and the absence of K-feldspar in the kyanite-rich subunit indicates lower  $aK^+$  than in the ore zone, although hydrothermal fluids clearly promoted marginal alteration and sulfidation of the wallrocks near the ore zones.

Fig. 2-13.

AFM projection showing the compositions of unaltered metapelites (circles, dark fill) and kyanite-rich transitional rocks (diamonds, light fill). Note that all rocks plot above the garnet-chlorite join.



Fig. 2-13.

#### Metamorphism of ore zone rocks

Ore zone mineral assemblages differ from those expected based on bulk rock compositions ignoring sulfur (Fig. 2-14). As discussed above, the lack of metamorphic index minerals at Hemlo resulted from sulfidation and alteration, and does not imply that mineralization post-dated peak metamorphism (e.g., Fleet and Pan, 1995). Therefore, the metamorphic evolution of ore zone mineral assemblages should be examined in the reduced KMASH system, which includes the most common ore zone mineral assemblage, K-feldspar-quartz-muscovite-biotite±kyanite. The elements Fe, Ca, Mn and Na are excluded as they are either depleted in these rocks or partitioned into pyrite. Kyanite-rich rocks plot within the Mg-chlorite-muscovite-kyanite subsection of the AKM (+H<sub>2</sub>O and quartz) triangle (Fig. 2-15). At higher temperatures muscovite and chlorite react to form kyanite and phlogopite as follows:

Mg-chlorite + muscovite = kyanite + phlogopite(9)

This reaction continues until either chlorite or muscovite are consumed. Due to the low concentration of Mg and the unavailability of Fe, chlorite was the first mineral stabilized to disappear. This reaction therefore the assemblage muscovite+kyanite+phlogopite, which is observed throughout the kyanite-rich subunit. Rocks that contain little or no Mg would have stabilized the assemblage muscovite+kyanite without biotite, which occurs locally in the kyanite-rich subunit. In KMASH space, potassically altered ore zone rocks plot in the K-feldspar-muscovitephlogopite field, which represents an assemblage that does not evolve during prograde metamorphism. Thus, the mineral assemblages in both ore zones and kyanite-rich

Fig. 2-14.

AFM projection showing the composition of ore zone rocks that contain >1.5 g/t Au. Based on these bulk rock compositions, metamorphic index minerals such as garnet, staurolite and/or kyanite should be present in addition to biotite.



Fig. 2-14.

Fig. 2-15.

Modified AKM projection showing the composition of hangingwall (squares) and footwall (diamond, dark grey fill) metasediments and ore zone rocks (circles, light grey fill). The projection is modified so that K-feldspar plots at the K apex; mineral compositions are in brackets. The arrow indicates the compositional variations during potassic alteration. (Lithogeochemical data from Williams-Jones et al., 1998).



Fig. 2-15.

wallrocks are non-diagnostic of peak metamorphic conditions and cannot be used as an argument against a post-peak metamorphic timing of mineralization (e.g., Fleet and Pan, 1995).

The effect of peak metamorphism on the ore zone silicate assemblage (Kfeldspar-muscovite-biotite-quartz±plagioclase) was limited to recrystallization, changes in mineral density, and incorporation of elements such as Ba and V. During metamorphic recrystallization, K-feldspar and biotite incorporated barium into their structure while V was taken up by muscovite and rutile. K-feldspar and quartz have a granoblastic texture which resulted from recrystallization during metamorphism, and micas recrystallized to form coarse-grained, oriented muscovite and locally biotite. However, the lack of typical metamorphic index minerals in equilibrium with this assemblage suggests that the effect of metamorphism was limited to exchange reactions, and that new minerals were not created by net transfer reactions. Similar observations can be made for sulfides, sulfates and oxide minerals. The transition from pyrite to pyrrhotite, which is frequently observed in high-grade rocks (Spear, 1993), did not occur at Hemlo, and Fe-oxides generally are absent from the ore zones. The fact that pyrite did not convert to pyrrhotite and/or participate in sulfide-silicate reactions indicates that high  $fS_2$  levels prevailed throughout peak metamorphism, and suggests that metamorphic fluids did not re-equilibrate or modify the previously altered and mineralized rocks. One possible explanation is that the shear zone, which hosts the ore zones was closed during peak metamorphism, and that the intergranular fluids that equilibrated with these rocks were not externally buffered. This is consistent with a

ductile setting during peak metamorphism (~630 °C, 6 kb; Heiligmann et al., Chapter 3) in which fluid moves by diffusion and not by advection.

#### The importance of barite

The effect of sulfidation during metamorphism has been recognized in sulfiderich ore zones such as those of massive sulfide deposits (e.g., Vokes, 1969; Lang, 1992; Rosenberg, 1998; Spry, 2000 and references therein), but is less well understood in mesothermal gold deposits. Mesothermal gold deposits usually do not contain enough sulfur to generate a pronounced sulfidation overprint. However, the Hemlo gold deposit has two volumetrically important sulfur minerals: pyrite, which is more abundant at Hemlo than in most hydrothermal gold deposits, and barite, which is present in both the Lower and Main ore zones. Isotopic data indicate that barite is of sedimentary origin (i.e. it was syn-sedimentary, and according to Cameron and Hattori (1985) was deposited from hydrothermal fluids venting onto the sea floor) and thus was not introduced with the mineralization (Thode et al., 1991). However, sulfur from barite was incorporated into pyrite (Thode et al., 1991), which suggests that the abundance of pyrite is, in fact, due to the dissolution of barite.

The substitution of Ba into silicates, intergrowths of sulfides and barite, and the occurrence of barite in late-stage veinlets and fractures supports the idea that barite dissolved locally, and buffered ambient fluids, well into the retrograde phase of metamorphism. The lack of evidence of intense  $H^+$  metasomatism in the ore zones, which is commonly associated with high-sulfidation epithermal deposits, implies more moderate  $fS_2$  that maintained a relatively steady but elevated level through the
dissolution of barite (BaSO<sub>4</sub> + 2H<sup>+</sup>  $\rightarrow$  Ba<sup>2+</sup> + H<sub>2</sub>S + 2O<sub>2</sub>). Buffering of *f*S<sub>2</sub> (and *f*O<sub>2</sub>) prevented the transformation of pyrite to pyrrhotite, and the partitioning of Fe from pyrite into silicate or oxide phases during peak metamorphism. As a consequence, pyrite (and thus Fe) was to all intents and purposes stable and inaccessible for metamorphic reactions, which explains why there are no other Fe-bearing minerals in the Hemlo ore zones.

#### Implication for exploration

Exploration for hydrothermal ore deposits in metamorphic terrains typically involves a search for textural and mineralogical evidence for hydrothermal alteration, because hydrothermally altered rocks present very much larger targets than the potentially associated economic mineralization. However, metamorphism and accompanying deformation generally destroy textural evidence for alteration, and alteration minerals are often transformed into minerals and mineral assemblages that are indistinguishable from those of commonly occurring metasediments or metamorphosed igneous rocks. For example, a propylitic alteration zone, characterized by the mineral assemblage chlorite+epidote±carbonates±pyrite is very similar mineralogically to a greenschist-facies metabasite. The problem is amplified if these rocks are subsequently deformed and metamorphosed under amphibolite-facies conditions. where the essentially bi-mineral they form assemblage amphibole+plagioclase. Clay minerals such as kaolinite and illite, that form during epithermal alteration, recrystallize to aluminosilicate and muscovite, which are common in metasedimentary rocks. However, metamorphosed alteration zones can be

identified by elevated sulfide (i.e., pyrite) abundances and changes in mineral assemblages that cut across lithological boundaries. In addition, bulk-rock geochemical analyses can identify zones of abnormal enrichment or depletion of elements during alteration, respectively.

At Hemlo, altered wallrocks exhibit several trends that might be useful in mineral exploration. Metamorphic index minerals, such as garnet and staurolite, are absent within metasedimentary ore zone rocks, but present in wallrocks, and kyanite, suppressed by high  $aK^+$  in the deposit, is abundant in the hangingwall due to sulfidation. Furthermore, pyrrhotite, the stable Fe-sulfide in amphibolite-facies metamorphic rocks, is common in the wallrocks but rare/absent in the deposit. A similar relationship is observed for rutile and ilmenite. Ilmenite is common in the wallrocks, but is replaced by rutile in the deposit. The proximity of the ore zone is indicated by the coexistence of pyrite, pyrrhotite, ilmenite and rutile.

Compositional variations in the vicinity of the ore zones include a depletion in the Fe/(Fe+Mg) ratios of Fe-silicates, and an increase in substitution of ore-related elements into minerals such as rutile (e.g., Sb and V) and staurolite (e.g. Zn) (Williams-Jones et al., 1998; this study).

Since the Hemlo deposit transects lithological boundaries, the disappearance of metamorphic index minerals, changes in mineral assemblages and mineralogical changes in sulfides and oxides are recognizable on an outcrop scale, and can serve as important vectors to economic mineralization. For example, mafic fragmental rocks at Hemlo contain the assemblage amphibole-plagioclase-quartz±garnet, and the altered

equivalent is characterized by biotite-muscovite-quartz  $\pm$  calcite  $\pm$  amphibole  $\pm$  plagioclase.

### Conclusions

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Metamorphic index minerals are absent from the altered metasediments that form most of the ore zone rocks because these minerals are not stable in the presence of the sulfide-sulfate-silicate-oxide assemblage. During peak metamorphism, the common ore zone assemblage biotite-muscovite-microcline-quartz recrystallized but did not form the index minerals normally expected in amphibolite-facies rocks. Their absence is therefore non-diagnostic of peak metamorphic conditions and misleading as to the timing of mineralization with respect to metamorphism.

Unusual mineral assemblages also occur in the transition between ore zone and hangingwall metasedimentary rocks. Pelitic metasediments in the vicinity of the deposit are 'high-Al' metapelites and thus did not undergo the classical Barrovian index mineral progression of chlorite  $\rightarrow$  biotite  $\rightarrow$  garnet  $\rightarrow$  staurolite  $\rightarrow$  kyanite  $\rightarrow$ sillimanite. 'High-Al' metapelites near ore zones formed an early aluminosilicate, followed by biotite in the weakly altered kyanite-rich subunit. Despite their proximity to potassically altered ore zone rocks and their unusual mineral assemblage, these rocks are not the product of argillic alteration, but rather formed via sulfidation of Mg- and Fe-poor rocks during prograde metamorphism and sequestration of Fe by pyrite.

The high degree of sulfidation at Hemlo, expressed by the lack of Fe-silicates and Fe-oxides, and the exclusive occurrence of pyrite as the stable Fe-sulfide in amphibolite-facies ore rocks, is rarely observed in lode gold systems, which generally

do not contain enough sulfur. This implies that barite played a pivotal role in the formation and modification of the sulfide-silicate-oxide mineral assemblage. The dissolution of barite added Ba to silicate minerals and strongly increased the stability of pyrite by raising  $fS_2$ . Pyrite in turn fixed Fe, and Fe was thus unavailable to participate in prograde metamorphic reactions. Mineralogical changes in passing from the wallrocks to the ore zone involve the alteration of ilmenite to rutile, and pyrrhotite to pyrite. In addition, biotite becomes more magnesium-rich, the Zn content of staurolite increases, X<sub>almandine</sub> decreases and X<sub>spessartine</sub> of garnet increases, and there is an increase in the proportions of muscovite and K-feldspar.

Potassic alteration and elevated  $fS_2$  conditions also affected the partially mineralized mafic fragmental subunit and led to the breakdown of amphibole to form biotite. Thus, the mafic fragmental unit is the altered equivalent of a heterogeneous mafic to conglomeratic sediment, and not a biotitized felsic rock.

The metamorphism of the Hemlo gold deposit and its alteration zones hampered the initial discovery of the deposit and is in large part responsible for the wide range of proposed depositional models and conflicting interpretations of timing relationships. Although altered rocks commonly have very different bulk compositions from their precursor lithologies, their metamorphosed equivalents may be quite similar and differ only in the proportions of metamorphic minerals. However, their true nature is revealed through detailed geological studies. Geochemical changes such as enrichment of K and depletion of elements such as Na and Ca may become evident from whole rock geochemical analyses, and mineralogical analyses may reveal decreases in the Fe/Mg ratios of Fe-bearing silicates or unusual compositions in

minerals such as staurolite and rutile. The recognition of metamorphosed alteration zones can greatly advance mineral exploration for other hidden deposits.

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The previous chapter investigated the evolution of ore zone rocks during prograde metamorphism. Hemlo ore zones differ from adjacent metasediments in that they generally lack metamorphic index minerals, an observation that has been used to argue for a post-peak metamorphic timing for mineralization. In addition, ore zone rocks contain unusually high concentrations of S, K and Fe, but are depleted in elements such as Ca, Mg and Mn. As a consequence, these mineralized and altered rocks evolve differently from country rocks during prograde metamorphism.

Although previous metamorphic studies at Hemlo generally concurred that metamorphism reached amphibolite-facies pressures and temperatures, there remains considerable uncertainty about the peak metamorphic conditions, the number of prograde episodes, and the relative timing of mineralization with respect to metamorphism. These issues are addressed in chapter III.

# **Chapter III**

# Metamorphic P-T-t relationships at the Hemlo Au deposit, Ontario: a re-evaluation of geothermobarometry and mineral equilibria

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#### Abstract

The Hemlo gold deposit, one of Canada's most important gold producers (95 million tons of ore, grading  $\sim 8$  g/t), has been overprinted by amphibolite-facies peak metamorphism. As a result, the alteration zones are recrystallized, any direct evidence of the mineralizing fluid is destroyed, the genetic model obscured, and the mineralization partially remobilized. Despite the importance of metamorphism for the deposit, there is still little agreement on the temperature-pressure conditions of peak metamorphism, and on whether there were one or two metamorphic events.

New estimates of metamorphic temperatures for metabasites (based on multiple analyses of amphibole-plagioclase pairs in individual rocks) average ~630°C. These temperatures vary little ( $\pm$  26°C), provide no evidence for a metamorphic gradient in the study area, and are interpreted to represent the peak of metamorphism. By contrast, garnet-biotite temperature estimates for metapelites (these rocks occur in the immediate vicinity of the deposit), are up to 150°C lower and vary greatly (locally by >100°C) depending both on the calibration method employed and the part of the garnet crystal analyzed (e.g., core versus rim). The latter suggests that garnet-biotite pairs generally continued to re-equilibrate after peak metamorphic conditions were attained. Temperatures calculated with the garnet-biotite geothermometer of Hodges and Spear (1982) yield results that are closest to those derived for metabasites (~500 and 650°C) from amphibole-plagioclase geothermometry, and are considered the most representative of peak metamorphic temperatures. Pressure calculations based on data for metabasites and metapelites, using a variety of geobarometers, average 5-7 kb, with

outliers at 3 and 8kb. This wide range of pressure estimates suggests that peak conditions were only locally preserved.

Correlations between the metamorphic framework, geochronological data and paragenetic sequences suggest that the main gold and molybdenite mineralization occurred during prograde metamorphic heating (2685-2677 Ma), and was converted to a partial melt during peak metamorphism (2678-2675 Ma). Retrograde metamorphic cooling coincided with progressive crystallization of the sulfide melt, which formed stibnite and gold-bearing quartz veins at temperatures below ~550°C (~2660 Ma), and continued to crystallize until the final melt was dominated by As-S at temperatures below~310°C (~2600 Ma). Minerals associated with late-stage, calc-silicate alteration, which are randomly oriented, also formed during retrograde metamorphism at a temperature of 400-450°C (2650-2630 Ma). This extensive remobilization suggests that pre- to syn-metamorphic gold deposits are favorable environments for telescoped ore zones distal from the original mineralization.

A single P-T-t path is proposed, with an initial sharp increase in pressure and slower prograde heating, consistent with the relatively short period of time between sedimentation and peak metamorphism (~10 Ma). Retrograde metamorphic cooling is characterized by a gradual decrease in pressure and temperature that lasted for ~80 Ma and averaged ~ 5°C per m.y. The single metamorphic cycle proposed in this study is consistent with several generations of porphyroblasts (e.g., aluminosilicates, and possibly two generations of garnet and staurolite) in the Hemlo area. Low temperature kyanite was preserved by the sulfidation overprint from the deposit, whereas a second generation of kyanite and the high-temperature polymorph sillimanite are common

elsewhere. In addition, different generations of garnet and staurolite formed because of the presence of both low-(Fe+Mg), 'high-Al' and normal, Barrovian metapelites.

### Introduction

The vast majority of shear zone-hosted gold deposits are thought to have formed in greenschist facies terrains, millions of years after peak metamorphism (e.g., Kerrich, 1993; Groves et al., 1998). However, this is not the case for the giant Hemlo gold deposit, Ontario, which is shear zone-hosted (e.g., Burk et al., 1986), but has been recrystallized and partly remobilized by amphibolite-facies metamorphism, and therefore formed pre- (to syn-) peak metamorphism (Burk et al., 1986; Kuhns et al., 1994; Williams-Jones et al., 1998; Powell et al., 1999). This timing of mineralization presents a major obstacle to the interpretation of ore genesis as (1) direct evidence of the mineralizing fluid (such as fluid inclusions) has been destroyed, (2) alteration mineral assemblages were modified, and thus the effects of alteration are more difficult to recognize (Heiligmann et al., Chapter 2), (3) the ore mineral assemblage and its distribution were modified by hydrothermal remobilization, and/or solid-state exsolution, and/or melting of sulfides (Kuhns et al., 1994; Powell and Pattison, 1997; Tomkins et al., 2003; Heiligmann et al., 2003; Tomkins et al., 2004), and (4) radiometric ages may have been reset, thereby obscuring timing relationships (e.g., Muir, 2002). It is thus not surprising that even now there is little agreement on the origin of the deposit.

Since its discovery in 1982, Hemlo has been described as a volcanic exhalative (Valliant and Bradbrook, 1986), epithermal (e.g., Patterson, 1984), porphyry (e.g., Kuhns et al., 1994), skarn or metamorphic replacement (e.g., Pan and Fleet, 1992, 1995), and mesothermal (-orogenic) deposit (e.g., Burk et al., 1986; Muir, 1997, 2002). The locally extensive remobilization of the ore and its association with low

temperature minerals such as realgar and stibnite, and calc-silicates such as prehnite, grossular and zoisite, led to an interpretation that mineralization post-dates peak metamorphism (e.g., Harris, 1989; Pan and Fleet, 1995). However, this interpretation is inconsistent with the association of much of the native gold with recrystallized potassic alteration assemblages. Geochronological interpretations of the timing of mineralization and alteration using Ar-Ar or U-Pb isotopic methods are complicated by the fact that minerals such as micas, hornblende, rutile and perhaps titanite record closure dates rather than crystallization ages, and that it is often difficult to distinguish among inherited, magmatic, metamorphic or hydrothermal minerals (e.g., Muir, 2002).

Early studies of the metamorphism concluded that the Hemlo area was subjected to a peak metamorphic temperature of ~585°C and a peak pressures of to ~7 kb (Burk et al., 1986; Burk, 1987), or 500 to 600°C and 4 to 6.5 kb, respectively (Kuhns et al., 1994; largely based on Kuhns, 1988; Table 3-1). These studies also postulated a less important, second metamorphic event (M2), based on the occurrence of reversely-zoned garnets, actinolitic/tremolitic rims on prograde hornblende, minor chlorite and epidote, and the presence of fibrolite. Burk et al. (1986) interpreted this second event to represent prograde metamorphism at lower pressure (5 kb) but not lower temperature, due to rapid uplift and erosion, and noted that M2 might have been continuous with M1. By contrast, Kuhns et al. (1994) attributed M2 to intrusion of the Cedar Creek Stock, an event which has subsequently been interpreted to have occurred synchronously with or even preceding M1 metamorphism (Corfu and Muir, 1989a; Muir, 2002; Davis and Lin, 2003). However, they also considered the possibility that M2 might represent the retrograde stage of M1 metamorphism, and was caused by the

Study	Metamorphic events	Т (°С)	P kb	Comment
Burk (1986)	M1 M2	585 585	7 - 8 5	Noted that the two metamorphic events may be prograde and retrograde stages of a single metamorphic cycle
Kuhns et al. (1994)	M1 M2	500-600 300-400	4 - 6.5 1 - 3.0	Both metamorphic events might be part of the same P-T loop
Pan and Fleet (1993)	M1 M2	500 550-650	6-6.5 4-5	Two prograde metamorphic events
Muir (1997)	M1 M2 M3	not constrained not constrained not constrained		Metamorphic events divided based on mineralogical, textural and U-Pb constraints
Powell et al. (1999)	M1	600-650 600	6 - 7 4 - 5	Single metamorphic event with prograde and retrograde stages

Table 3-1. Results from previous metamorphic studies at Hemlo.

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resetting of mineral equilibria due to late-stage fluid infiltration. Estimated P-T conditions for the M2 stage vary from 585°C and 5 kb (Burk et al., 1986), to 300-400°C and 1-3 kb (Kuhns et al., 1994).

The strongest proponents of a metamorphic history involving two clearly separate prograde events have been Pan and Fleet (1993), who based their conclusions largely on data from the White River area, located 10-15 km southeast of Hemlo. They estimated the pressure-temperature conditions of the first prograde event (M1) at 500°C and 6-6.5 kb, and those of M2 as between 520°C and 3-3.5 kb, and 550-650°C and 4-5 kb. Their reasons for proposing two prograde events were (1) the presence of andalusite, sillimanite and kyanite, and (2) a P-T path derived from a single zoned garnet porphyroblast with mineral inclusions (Pan and Fleet, 1993). Pan (1990) considered that the occurrence of andalusite and sillimanite was indicative of Buchan zone metamorphism (low P, defined by the index minerals staurolite, cordierite, and alusite and sillimanite), and concluded that kyanite (the high-P  $Al_2SiO_5$  polymorph) was a metastable remnant from a previous metamorphic event (M1). Multiple metamorphic episodes were also proposed by Muir (1997), who, in a regional study of the Hemlo deposit area, tentatively interpreted textural relationships among index minerals to be consistent with three metamorphic episodes. However, this study did not include thermobarometric calculations, and therefore did not define peak metamorphic conditions.

Powell et al. (1999) were the first to unequivocally postulate a single metamorphic event, and based their interpretations on the postulated occurrence of two generations of andalusite, which they argued were separated by the development of

kyanite and then sillimanite. They estimated the peak metamorphic conditions to have been 600-650°C and 6-7 kb from petrogenetic grid constraints (the staurolite-out reaction) and recalculation of the geothermobarometric data of Burk (1987).

As is evident from the preceding discussion, there is little agreement on the P-T conditions of peak metamorphism, and on whether there were one or two metamorphic events. Moreover, previous studies were either based largely on data and interpretations from the White River area, located 10 to 15 km from the deposit (Pan and Fleet 1993), or on limited data restricted to the immediate vicinity of the deposit (Burk et al., 1986; Kuhns et al., 1994; Powell et al., 1999); the studies by Kuhns et al. (1994) and Powell et al. (1999) were largely based on mineral equilibria and recalculations of garnet-biotite data from Burk (1987). In this paper, we report new geothermobarometric data from wallrocks in the deposit area, as well as data from regional exposures located up to 3 km from the deposit. We use these data to determine metamorphic conditions, and to evaluate the possibility of multiple prograde episodes. We also investigate the effect of retrograde metamorphism on mineral geothermometers and mineral equilibria, and propose a depositional framework for the area that includes pre-peak metamorphic mineralization and retrograde remobilization of the ore. Finally, the evolving P-T conditions are related to the absolute timing of crystallization of specific mineral assemblages (based on previous geochronological studies) and used to construct a P-T-t path for the deposit.

#### **Regional Geology**

The Hemlo gold deposit (which contains 95 million tons of ore grading 8 g/t (Schnieders et al., 2000) and is one of Canada's most important gold producers) is located in the Hemlo-Heron Bay greenstone belt of the Wawa subprovince in the Superior Province (Fig. 3-1). The belt hosts a sequence of Archean volcano-sedimentary rocks intruded or bounded by felsic to intermediate batholiths, plutons and stocks (Williams et al., 1991; Muir; 1997, 2002). Sedimentary rocks comprise pelites, siltstones, arenites, wackes, marls, and conglomerates, which locally exhibit depositional features such as grading and cross-bedding; multiple deformational events and metamorphic recrystallization have obscured many primary features. Metapelitic units occur in the immediate vicinity of the ore zones and south of the Hemlo fault.

Calc-alkaline and tholeiitic mafic volcanic rocks are abundant adjacent to the Pukaskwa gneissic complex, near the Hemlo fault, and north of the deposit. Locally preserved primary features include variolitic and pillowed units, but most rocks are massive, and have been recrystallized to amphibolites during regional metamorphism. Garnetiferous amphibolites are locally present in the deposit area, but occur mainly near alteration zones, and might be related to late-stage fluid infiltration.

Felsic to intermediate volcanic and sub-volcanic rocks occur north of the Hemlo fault (Muir, 1997). Volcanic rocks are variably fragmental, whereas subvolcanic units are massive (Muir, 1997). A quartz-feldspar-phyric unit extends from the ore zones to about one km east of Botham Lake, and contains both massive and fragmental sub-units. The effects of metamorphism, deformation and premetamorphic alteration make the origin of this lithology contentious, and proposed

Figure 3-1.

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Simplified geological map the Heron Bay-Hemlo greenstone belt, showing the location of the Hemlo gold mines (square symbols in box localizing Figure 2) and major intrusions (modified from Muir, 1997).





precursors include a porphyritic intrusion (e.g., Kuhns et al., 1994; Johnston, 1996) and an intrusive-extrusive unit (Muir, 1997; 2002).

Regional metamorphism formed mineral assemblages in metabasites and metapelites that are indicative of greenschist/lower amphibolite to upper amphibolite facies conditions. There is a general increase in metamorphic grade from west to east, as well as near some plutonic margins (Jackson, 1998). Prograde metamorphism in metabasites is characterized by decreases in chlorite and actinolite abundances and increases in the abundance of hornblende, whereas metapelitic assemblages vary from garnet-chlorite and staurolite, to garnet-biotite-sillimanite (Jackson, 1998).

The largest intrusion in the deposit area is the Pukaskwa gneissic complex, located ~2.5 km south of Hemlo, which consists of a composite granitoid batholith with hornblende-bearing tonalite, diorite and granodiorite (Muir, 1997); the complex contains the oldest rocks in the area (Corfu and Muir, 1989a, b). Other intrusions include the Cedar Lake pluton and Cedar Creek stock, located ~300 m west of the deposit, and the Gowan Lake and Heron Bay plutons located to the northeast and southeast, respectively (Fig. 3-1). The Cedar Lake and Heron Bay plutons and the Cedar Creek stock are granodioritic, whereas the Gowan Lake pluton varies from diorite-granodiorite to quartz monzodiorite (Beakhouse, 1998). There are also several small granodiorite bodies, which occur ~3 km east of the deposit, (e.g., Botham Lake stock; Muir, 1997).

Approximately 100 m south of the deposit, the area is cut by the northeastsouthwest trending Hemlo fault, a major regional structure which has been tentatively interpreted to separate juxtaposed lithotectonic assemblages (Williams et al., 1991). Three other fault/shear zones that are roughly parallel to the Hemlo fault zone also occur within the vicinity of the deposit. The Moose Lake fault and the Lake Superior shear zone coincide with the Lower and Main ore zones at Hemlo. The Cedar Creek fault is largely inferred, and contains an altered but unmineralized sulfide zone (Muir, 1997).

#### **Deposit scale geology**

Gold mineralization at Hemlo occurs within two steeply dipping ore zones that are neither stratabound nor, strictly speaking, stratiform (Muir, 1997) (Fig. 3-2). Lin (2001) interpreted these zones to be on the opposing limbs of a proto-sheath fold, a conclusion that is consistent with lithogeochemical similarities of hangingwall and footwall rocks (Bodycomb et al., 2000). Both the Lower (footwall) and Main (hangingwall) ore zones generally coincide with baritic sediments. Footwall metasediments grade into the Lower ore zone, which is separated from the Main ore zone by a quartz-feldspar porphyry unit (Fig. 3-3). The Main ore zone locally overprints a heterogeneous mafic fragmental unit, which occurs only in the hangingwall at the Golden Giant and David Bell mines, and grades into hangingwall metasedimentary rocks.

#### Wallrocks

Footwall and hangingwall rocks consist mainly of interlayered metasediments that include the metamorphosed equivalents of sandstones, greywackes, marls and pelites. Metamorphosed sandstones and greywackes consist mainly of quartz-feldspar-

Figure 3-2.

Geological map of the Hemlo area (modified from Muir, 1997), showing the location of mines and distribution of mineralization (black). Note that the Lake Superior shear zone (LSSZ) and Moose Lake fault zone (MLFZ) coincide with the Main and Lower ore zones, respectively.



Fig. 3-2.

Figure 3-3.

Simplified cross-section though the Golden Giant mine, which is located approximately in the center of the deposit. Mineralization occurs at the contact between footwall metasediments (including wackes, marls and pelites) and quartz-feldspar porphyry rocks (Lower ore zone), and between the quartz-feldspar porphyry and hangingwall metasediments (including wackes, marls and pelites) and the mafic fragmental unit (Main ore zone). Note that the mafic fragmental unit only occurs in the hangingwall, and is less extensive or absent in other parts of the deposit (modified from Sutcliffe, 1998).

# LEGEND



Quartz-feldspar porphyry ("Moose Lake Porphyry")

Ore zones (Main and Lower)



Mafic fragmental unit

Porphyry dykes

Metasedimentary (pelites, sandstones, wackes, marls etc) and reworked volcaniclastic rocks



Fig. 3-3.

muscovite and quartz-feldspar-biotite-muscovite schists, respectively. Marlv sediments are characterized by dark-green layers in hangingwall and footwall metasediments. and are composed mainly of amphiboles (hornblende, actinolite/tremolite), plagioclase, quartz, biotite and chlorite, with minor calcite, epidote, garnet, zoisite, titanite and diopside. These layers are locally boudinaged, occur generally parallel to bedding planes, and display penetrative foliation. Metapelites contain metamorphic index minerals that include biotite, garnet, staurolite and kyanite/sillimanite, except in the vicinity of the ore zones where contents of Fe and Mg are low compared to average pelites (e.g., Shaw, 1956), and the development of the classic Barrovian sequence of index minerals (biotite->garnet->staurolite->kyanite->sillimanite) is suppressed. Instead, these rocks evolved like high-Al pelites in which minerals order andalusite/kyanite->staurolite->garnet->biotiteappear in the >kyanite/sillimanite (Heiligmann et al., Chapter 2.).

The mafic fragmental unit is locally mineralized, and includes heterogeneous mixtures of mainly felsic clasts in an intermediate to mafic matrix; its precursor has been interpreted to be a mafic volcaniclastic rock (Kuhns, 1988), a mafic conglomerate (Burk et al., 1986), a hydrothermal breccia (Johnston, 1996), or a biotitized felsic fragmental rock (Lin, 2001). Unaltered segments of this unit contain amphibole, plagioclase, muscovite and quartz, and minor magnetite, garnet, epidote and pyrrhotite.

#### Ore zone rocks

Ore zone rocks do not represent primary lithologies, but rather are the metamorphosed equivalents of altered and mineralized sedimentary, mafic fragmental,

and to a lesser extent quartz-feldspar porphyry rocks (Williams-Jones et al., 1998). Both the Lower and Main ore zones coincide locally with baritic sediments that occur near the contacts of metasedimentary and quartz-feldspar porphyry units. Barite-rich rocks have been variably interpreted to be sedimentary (Valliant and Bradbrook 1986; Burk, 1987; Kuhns, 1988; Williams-Jones et al., 1998), or hydrothermal in origin (Harris, 1989; Johnston, 1996; Muir, 2002). However, unmineralized barite occurrences from the same stratigraphic horizon but several kilometers away from the deposit have similar <sup>32</sup>S/<sup>34</sup>S and <sup>87</sup>Sr/<sup>86</sup>Sr ratios to Hemlo barite (Cameron and Hattori, 1985; Thode et al., 1991). These stratigraphic and isotopic relationships suggest that barite formed by exhalative activity within a restricted sedimentary basin, and that barite is sedimentary in origin. Massive to semi-massive baritic rocks are characterised by recrystallized, fine-grained, sugary textured barite that forms strongly deformed layers and breccias that contain locally feldspathic, siliceous and muscovitic ore fragments. In addition to barite, well-mineralized baritic ore is composed of quartz, Ba-microcline and pyrite, with lesser Ba-V-muscovite, plagioclase and Ba-Vbiotite, and traces of calcite, chlorite and titanite.

Most gold mineralization occurs in rocks that are either microcline- or muscovite-rich. Feldspathic ore consists of relatively fine-grained, granoblastic rocks composed of barian microcline, quartz, pyrite and Ba-V-muscovite, with minor barite, plagioclase, biotite, calcite, rutile, titanite and tourmaline. These rocks exhibit significant textural and compositional heterogeneity, including mica- and quartz-rich layers, and variable pyrite concentrations. Muscovitic ore is characterized by recrystallized, granoblastic quartz, Ba-V-muscovite and Ba-microcline schists, with

locally abundant pyrite, and minor barite, Ba-V-biotite, tourmaline, calcite, rutile, and titanite.

#### Quartz-feldspar porphyry unit

The Lower and Main ore zones are separated by a quartz-feldspar porphyry that has been variably interpreted as the metamorphosed equivalent of quartz-plagioclasephyric felsic extrusive (pyroclastic), reworked volcaniclastic, and lesser intrusive rocks (Muir, 1997; Williams-Jones et al., 1998) or as entirely intrusive (Kusins et al., 1991; Kuhns et al., 1994; Johnston, 1996). This unit consists mainly of quartz, plagioclase, muscovite and microcline, and was foliated and recrystallized during regional metamorphism. However, due to a lack of metamorphic index minerals, these rocks cannot be used for geothermobarometric studies.

#### Dikes and sills in the ore zones

The ore zones are transected by a series of felsic to mafic dikes and sills, most of which were emplaced after mineralization. Dacitic sills are typically foliated, locally boudinaged, and cross-cut mineralization; they have not been related to any larger intrusions in the deposit area. Pyroxene- and plagioclase-phyric diabase dykes of late Proterozoic age also transect the ore zones. In addition to the above, aplitic dikes occur locally in the deposit, and although generally unmineralized, one altered and mineralized example has been dated at 2677 ( $\pm$ 1.5) Ma (Davis and Lin, 2003). However, it remains unclear whether this dyke was mineralized during the main
mineralization event or was affected by later remobilization of gold and related minerals (Robert and Poulsen, 1997; Davis and Lin, 2003).

## Alteration and mineralization

Gold mineralization can be divided into three different events/associations. Most of it occurs as disseminated, Ag- and Hg-bearing native gold, which is accompanied by molybdenite. Although pyrite is ubiquitous in these rocks, there is no direct correlation between pyrite abundance and gold grade. This disseminated Au-Mo mineralization and related potassic alteration is interpreted to represent the initial and most important gold concentrating event (e.g., Williams-Jones et al., 1998). In addition, gold is also commonly associated with sulfides such as stibnite, zinkenite, and realgar, which are locally abundant in deformed and boudinaged quartz-veins and pods, but also occur at silicate grain boundaries and as solid inclusion trails throughout the ore zones.

Finally, minor gold occurs in undeformed veins and replacement zones that locally cross-cut tectonic fabric, and are associated with calc-silicate alteration. Rocks affected by calc-silicate alteration contain calcite, titanite, amphibole, epidote, zoisite, diopside, pumpellyite and prehnite. This association has been used to support the interpretation that Hemlo is a skarn (Pan and Fleet, 1991, 1992) or late-stage replacement deposit (Pan and Fleet, 1995). However, calc-silicate veins in the deposit are volumetrically minor, and thus do not account for appreciable gold mineralization.

Potassic alteration, represented by microcline-rich rocks, dominates the central and highest grade parts of the ore zones, and this central zone is surrounded by lower

grade muscovitic ore with disseminated microcline that is interpreted to represent a zone of lower potassium activity (Heiligmann et al., Chapter 2). During peak metamorphism, potassic alteration minerals recrystallized, giving rise to granoblastic annealed textures (such as triple junctions) in microcline-rich rocks and foliated muscovite schists (e.g., Burk, 1987, Kuhns, 1988; Williams-Jones et al., 1998). Sulfidation of these ore zone rocks preferentially partitioned Fe into pyrite, and inhibited the formation of Fe-silicates and Fe-oxides (Heiligmann et al., Chapter 2). In hangingwall pelitic sediments, the alteration-sulfidation halos led locally to the formation of quartz, kyanite, muscovite, pyrite  $\pm$  biotite-bearing schists (Heiligmann et al., Chapter 2).

The mafic fragmental unit is locally mineralized and, where this is the case, is relatively biotite-rich. Mineralized mafic fragmental rocks also contain abundant quartz and microcline, and subordinate barite, pyrite, muscovite and plagioclase. The origin of the biotite has been attributed to biotitization of a felsic precursor unit (e.g., Johnston, 1996; Lin, 2001). However, unaltered mafic fragmental rocks contain amphibole, which is locally altered to biotite at the alteration front (Heiligmann et al., Chapter 2), and therefore, the biotite simply reflects alteration of a mafic precursor lithology.

#### Structure

Numerous studies have investigated the structural history of the deposit area (Burk, 1987; Kuhns, 1988; Kuhns et al., 1994; Michibayashi, 1995; Muir, 1997, 2002; Lin, 2001). These studies describe multiple deformation events that are difficult to

correlate (cf., Muir, 2002), but the most recent studies by Muir (1997, 2002) and Lin (2001) propose a series of four (and possibly up to six) episodes of deformation and faulting (Table 3-2).

An early D1 event produced small-scale isoclines and sheath folds, and was followed by D2, which was characterized by sinistral shearing and small- to large-scale folding, as well as development of a penetrative S2 fabric. Strain resulting from a large-scale, northwest-directed transpression (D3) resulted in crenulation and Z folds and fabrics. A fourth episode (D4) related to northwesterly compression produced kink folds, and was followed by D5 and possibly D6, inferred from shearing in Paleoproterozoic and Mesoproterozoic dikes (Muir, 2002). According to Muir (1997, 2002), mineralization occurred during D2 deformation, and peak metamorphism coincided with the D2 and possibly D3 events. By contrast, Lin (2001) proposed that mineralization occurred prior to or early in the D2 stage (referred to by him as 'G2') and that peak metamorphism was late during D2 or post-D2.

#### Paragenetic sequences

The timing of mineralization at Hemlo was interpreted to be pre-metamorphic by Valliant and Bradbrook (1986), Goldie (1985) and Powell et al. (1999), and pre- to syn-peak metamorphic by Burk (1987), Kuhns (1988) and Michibayashi (1995). Johnston (1996) also concluded that mineralization was pre-peak metamorphic, but suggested that it occurred after regional folding. By contrast, Walford et al. (1986) and Muir (1997) presented a syn-metamorphic and syn-deformational model for ore formation. Mineralization was interpreted to be post-peak metamorphic but syn-

Deformation event	Burk (1987)	Kuhns et al. (1994)	Lin (2001)	Muir (1997, 2002)		
D1	Early deformation: broadly N-S directed compression which coincided with amphibolite facies metamorphism	Pre-peak metamorphic isoclinal folding	Early folding	Speculatively interpreted as early low-angle thrusting; small scale, isolated (remnant?) intrafolial isoclines (F1)		
D2	Late deformation: right- lateral shearing; formation of Z-type parasitic folds	Development of large-scale (syn- peak metamorphic) isoclinal folding and post-peak ductile- brittle shearing and faulting. Development of penetrative foliation	Sinistral transpression, development of camp scale folds and S2 foliation	Regional folding of the greenstone belt into small- to large scale, S-shaped folds (F2); a variety of styles of schistosity and cleavage (S2) and linear features (L2).		
D3		Late brittle faulting	Oblique detral shearing, development of crenulation cleavage	Z-shaped folds, ductile dextral shear, development of locally penetrative schistosities		
D4			Development of kink bands	Dextral and sinistral kink folds		
Timing of gold mineralization	Syn-peak metamorphic	Pre-peak metamorphic	Pre-peak metamorphic (mineralization before or early D2; peak metamorphism during or post-D2)	Pre-peak metamorphic		

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Table 3-2. Summary of structural constraints

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Note that deformational episodes described in different studies are difficult to correlate. Studies by Muir (1997, 2002) and Lin (2001) also describe or infer additional episodes of brittle faulting 146

deformational by Hugon (1986), and post-peak metamorphic by Harris (1989), White and Barnett (1990), and Pan and Fleet (1992, 1993, 1995).

Remobilization of gold and other elements has modified the original deposit, and Sb-, As- and Hg-bearing assemblages have been interpreted to represent either a later stage of the original Au-Mo event (Kuhns, 1988), "retrograde metamorphic remobilization" (Burk, 1987), remobilization during late deformation (Michibayashi, 1995), retrograde exsolution (Powell and Pattison, 1997), or remobilization by a sulfide melt (Tomkins et al., 2003, 2004; Heiligmann et al., 2003). Post-peak metamorphic calc-silicate alteration was interpreted by Pan and Fleet (1992, 1995) to be the host of most gold mineralization; the paragenetic sequence of Pan and Fleet (1995) postulated three stages ("A1" to "A3") of post-peak metamorphic alteration, but these are incompatible with sequences proposed by most other studies. The early A1 calc-silicate "alteration" event of Pan and Fleet (1995) is generally recognized as the product of metamorphism, and the A2 potassic event as of pre-peak metamorphic age (cf., Muir, 1997; Williams-Jones et al., 1998). Realgar and cinnabar were included in the A3 event, although these minerals occur in areas unaffected by calc-silicate alteration. Kuhns (1988) distinguished two stages of mineralization, namely a primary ore stage with associated potassic alteration that was pre-peak metamorphic, and a later remobilization stage that occurred during retrograde metamorphism, and is represented by minerals such as stibnite and realgar.

Williams-Jones et al. (1998) and Heiligmann et al. (2003) have proposed a paragenetic sequence for the ores that includes a primary gold mineralization stage and two subsequent stages of gold remobilization. Primary gold mineralization occurred

prior to peak metamorphism, was associated with potassic alteration and deposited native gold, molybdenite, pyrite and related sulfide and sulfosalt minerals. This mineralization was remobilized during peak metamorphism (~630°C) as a result of the formation of a sulfide liquid from the melting of primary ore minerals, including Hgbearing gold, the exsolution of Au, Sb and As from pyrite, and S derived from hydrothermal fluids (Heiligmann et al., 2003). During retrograde metamorphism, the sulfide melt crystallized progressively until temperature dropped below ~300°C, at which point the remaining melt was dominated largely by As and S, and formed realgar and orpiment (Heiligmann et al., 2003). A second, volumetrically minor remobilization and calc-silicate alteration occurred at ~400°C.

# Geothermobarometry

#### Methodology

Geothermobarometric calculations focused on metabasites and metapelites, which are relatively abundant in the Hemlo area, and are well suited for this purpose. Pressures and temperatures were calculated for wallrocks, adjacent to the mineralization, to determine the metamorphic setting of the Hemlo gold deposit, but also for regional metamorphic rocks (up to ~3 km from the deposit) in order to evaluate metamorphic gradients and possible fluid-driven re-equilibration of mineral assemblages in the vicinity of the ore zones. The latter is especially pertinent at Hemlo as the area is transected by at least four fault and shear zones, which may have served as conduits during late-stage fluid infiltration.

Temperature estimates were based on the amphibole-plagioclase geothermometer in metabasites, and the garnet-biotite exchange reaction in metapelites. The former used the calibration of Holland and Blundy (1994) for the reaction

#### edenite+albite = richterite+anorthite

which is applicable at temperatures between 400 and 1000°C and pressures between 1 and 15 kb; the estimated error is  $\pm 40$ °C (Holland and Blundy, 1994). Amphibole stoichiometry was determined using the method of Holland and Blundy (1994), which accounts for vacancies and constrains ferric/ferrous iron ratios.

There are several well-documented calibrations for the garnet-biotite geothermometer, including those based on experiments, such as that of Ferry and Spear (1978) and Perchuck and Lavrent'eva (1983), and those empirically derived such as that of Thompson (1976). The calibration of Ferry and Spear (1978) was subsequently expanded to allow for quaternary (Fe-Mg-Mn-Ca) garnet compositions (Hodges and Spear, 1982; Berman and Aranovich, 1996, TWQ). Chipera and Perkins (1988) evaluated these calibrations and found that the calibration of Perchuk and Lavrent'eva (1983) yielded the most accurate results for Fe-rich garnets (Fe/(Fe+Mg) >0.7). However, although most garnet at Hemlo has high almandine/pyrope ratios (>0.8), relatively high proportions of spessartine (up to 18%  $X_{spes}$ ) and grossular (up to 13%  $X_{gros}$ ) are common and require more complex mixing models, such as those proposed by Hodges and Spear (1982) and Berman (1990).

Most geobarometers applicable to mafic rocks are based on mineral assemblages involving garnet, which were rarely observed in the metabasites, except in

zones of obvious fluid infiltration. Therefore, pressures were calculated using the TWQ internally consistent database for mafic rocks (Berman, 1988; Berman, 1990; Mader et al., 1994), which yields good intersections if the minerals are in equilibrium, and poor ones in partly re-equilibrated rocks.

Pressure estimates for metapelites were based on GASP (garnetaluminosilicate-silica-plagioclase) and GPMB (garnet-plagioclase-muscovite-biotite) equilibria, and TWQ equilibrium calculations. The GASP geobarometer is based on the reaction

grossular + 2 kyanite/sillimanite + quartz = 3 anorthite

and was calibrated on Ca-rich, granulite-facies rocks (e.g., Ghent, 1976). Since garnet in the Hemlo area is generally dominated by almandine and the  $X_{gros}$  component is less than ~14 %, errors associated with the use of this geobarometer are likely to be considerable.

The GPMB equilibrium is calibrated for Mg- and Fe-endmembers, and is based on the reactions

grossular+pyrope+muscovite = 3 anorthite+phlogopite (Hodges and Crowley, 1985) grossular+almandine+muscovite = 3 anorthite+annite (Hodges and Crowley, 1985; Powell and Holland, 1988)

TWQ calculations used the updated 2.1 version of the program (Berman, 1988, 1991).

## Sulfidation-oxidation buffering and P-T estimates

The high sulfur activities, that occur frequently during the metamorphism of ore deposits such as Hemlo, affect the evolution of mineral assemblages by

partitioning Fe into sulfides (Heiligmann et al., Chapter 2). However, geothermobarometers are commonly dependent on Fe exchange between minerals. For example, in metapelites containing the assemblage garnet-plagioclase-rutile-aluminosilicate-ilmenite-quartz, both the GRIPS (garnet-rutile-ilmenite-plagioclase-silica) and GRAIL (garnet-rutile-ilmenite-aluminosilicate-silica) geobarometers (e.g., Bohlen and Liotta, 1986; Bohlen et al., 1983, respectively) are influenced by the exchange of Fe between garnet and ilmenite. The former geobarometer is based on the equilibrium:

$$Ca_{3}Al_{2}Si_{3}O_{12} + 2 Fe_{3}Al_{2}Si_{3}O_{12} + 6TiO_{2} = 6 FeTiO_{3} + 3 CaAl_{2}Si_{2}O_{8} + 3 SiO_{2}$$

grossular almandine rutile ilmenite anorthite quartz and the latter on:

 $Fe_3Al_2Si_3O_{12} + 3TiO_2 = 3FeTiO_3 + Al_2SiO_5 + 2SiO_2$ 

almandine rutile ilmenite aluminosilicate quartz

The problem in applying these equilibria near ore deposits is well illustrated at Hemlo, where the distribution of Fe is controlled mainly by high sulfur fugacities, which preferentially partitioned Fe into pyrite. Garnet and ilmenite are absent in the ore zones, whereas at the outer margin of the alteration envelope, garnet, ilmenite and rutile coexist; in unaltered rocks, ilmenite and garnet are stable but rutile is absent. This suggests that the primary control on the Fe distribution between garnet and ilmenite was sulfur fugacity (thus Fe availability) rather than pressure. In addition, ilmenite re-equilibrates quickly during retrograde metamorphism, leading to underestimates of peak conditions. Consequently these assemblages are unlikely to have been in equilibrium at Hemlo, and geothermobarometric calculations based on

them are unreliable. Geothermometers that involve biotite (such as the garnet-biotite exchange reaction) generally assume an infinite reservoir of biotite that preserves peak metamorphic conditions. This assumption may not be valid at Hemlo as, at least locally, the biotite content of the metapelites is very low. Furthermore, Fe/(Fe+Mg) ratios are also influenced by sulfidation reactions which preferentially partition Fe into sulfides, and consequently may lead to incorrect temperature estimates, if high  $fS_2$  levels persist to peak metamorphism and garnet and biotite did not properly equilibrate. Metapelites in the vicinity of the deposit, which yield abnormally low temperatures, locally contain staurolite with significant Zn, and biotite with appreciable Ba, indicating that the rocks were affected by marginal alteration and sulfidation associated with mineralization.

An additional, potential source for erroneous P-T data at Hemlo is the local overprint by calc-silicate alteration. As many geobarometers are based on the Ca exchange between garnet and anorthite, late-stage infiltration of Ca may modify peak metamorphic ratios and yield unreasonable temperatures and pressures.

#### **Temperature**

Estimates of metamorphic temperatures for the metabasites were based on multiple analyses of amphibole-plagioclase pairs in individual samples and average  $\sim 630^{\circ}$ C (Table 3-3a). These temperatures vary little (± 26°C) and provide no evidence for a metamorphic gradient in the study area. Furthermore, their consistency suggests that they represent the peak of metamorphism.

	Number of	ber of Average	
Sample #	analyses	5 kb	6 kb
970709-1	16	607	602
970709-12	17	623	618
971007-7	6	680	675
971008-1	14	658	653
971009-9	8	665	660
981004-10	12	644	639
981004-15	13	614	609
981004-21	12	617	612
981004-24	14	631	626
981004-26	10	618	613
981005-15	10	635	630
981005-5	9	650	645
981005-7	8	578	573
981005-9	16	607	602
981009-5	17	677	672
NGS-51-205.5	8	621	616
T226-28.8	6	662	· 657
T95-9-402.7	10	634	629

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Table 3-3a. Amphibole-plagioclase geothermometry using the calibration of Holland and Blundy (1994).

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Sample	TWEEQU assemblage	P (kb)	Т (С)
970709-4a	Alm-Prp-Grs-Tr-FeTr-Ts-FeTs-qtz	6	620
970709-4b	Alm-Prp-Grs-Tr-FeTr-Ts-FeTs-qtz	5	620
7-35-52.1	Alm-Prp-Grs-Tr-FeTr-Ts-FeTs-gtz	6.3	626
7-35-52.1b	Alm-Prp-Grs-Tr-FeTr-Ts-FeTs-qtz	6.9	630
971007-1	Alm-Prp-Grs-Tr-FeTr-Ts-FeTs-atz	53	677
971007-1b	Alm-Prp-Grs-Tr-FeTr-Ts-FeTs-qtz	5.1	577

Table 3-3b. TWEEQU pressure and temperature data for selected mafic assemblages.

alm - almandine, prp - pyrope, grs- grossular, tr - tremolite, ts - tschermakite, qtz - quartz, FeTs - ferro-tschermakite, FeTr - ferro-tremolite

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Amphibole-plagioclase pairs in the vicinity of igneous intrusions generally do not yield significantly higher temperatures. An exception is a ~700°C estimate close to the Pukaskwa gneissic complex, that could be due either to contact metamorphism or disequilibrium. Unusually high temperatures (~700°C) were also obtained locally from rocks collected close to faults, suggesting disequilibrium due to fluid infiltration.

Temperature estimates for the metapelites were based on samples collected in the immediate deposit area, and generally are lower than those for the mafic rocks. Those based on the calibration of Hodges and Spear (1982) vary between ~500 and 650°C, whereas they vary between ~475 and 625°C and ~520 and 610°C using the calibrations of Ferry and Spear (1978) and Perchuck and Lavrent'eva (1983), respectively (Table 3-4). Thus temperatures calculated with the garnet-biotite geothermometer of Hodges and Spear (1982) yield results that are closest to those derived for metabasites from amphibole-plagioclase geothermometry.

The large variation in the temperatures estimated using garnet-biotite geothermometry compared to that for temperatures estimated by amphiboleplagioclase geothermometry indicates that garnet-biotite pairs generally continued to re-equilibrate after peak metamorphic conditions were attained. This can be seen from the fact that temperatures based on rim compositions of garnet were as low as 500°C, whereas core compositions from the same crystal yielded temperatures as high as 610°C (Fig. 3-4).

A common cause for re-equilibration in metapelites is diffusion, which leads to a flattening of zoning profiles (e.g., Yardley, 1977), and may actually cause the calculated temperatures to decrease with increasing grade from the garnet to the

	Lithology	Garnet-biotite geothermometry			TWEEQU data		Other geobarometers			
Sample #		Dasg 91 T (°C)	FS 78 T (°C)	HS 82 T (°C)	PL 83 T (°C)	T (°C)	P (kb)	GASP P (kb)	GPMB-Mg P (kb)	GPMB-Fe P (kb)
440NQ-34-4.3-1	metapelite	624	625	652	609	650	4.9	3.3	4.8	3.8
T226-182.5-(1a)-1	metapelite	606	584	609	587					
970720-4-(1)-1	metapelite	576	617	658	605					
551-1198.7-(1a)-1	metapelite	565	584	617	587					
T226-8-8	metapelite	557	555	603	571					
T226-175-(3)-1	metapelite	581	532	558	558					
970729-5-(1a)-1	metapelite	572	558	596	572					
970720-1-5	metapelite	618	575	605	582					
10-6-65.4-(1)-1	metapelite	510	509	535	544	625	7.0	5.14		
970710-4-(1)-1	metapelite	540	571	610	580					
8-44-321.4-33	metapelite	528	543	580	564					
T226-135.3-1	metapelite	508	497	522	537	585	5.8	5.2	5.9	5.0
T221-42.5-18	metapelite	477	473	496	523	565	6	5.4	6.1	5.1
970705-3-1	metapelite	504	472	509	522					
T226-182.6 a	metapelite							5.6	6.57	5.50
970720-5 1b	metapelite							7.23	7.05	6.09
NGS-551-1198.7 1b	metapelite							7.06	8.07	6.64
duplicate									8.23	6.88
970709-4a	metabasite					620	6			
970709-4b	metabasite					620	5			
7-35-52.1	metabasite					626	6.3			
7-35-52.1b	metabasite					630	6.9			
971007-1	metabasite					577	5.3			
971007-1b	metabasite					550	5.1			

Table 3-4. Temperature-pressure conditions of peak metamorphism calculated from metapelites.

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Dasg 91 = Dasgupta et al., 1991; FS 78 = Ferry and Spear, 1978; HS 82 = Hodges and Spear, 1982; PL 83 = Perchuck and Lavrent'eva, 1983

Figure 3-4.

Apparent temperatures across zoned garnet crystals, estimated using different calibrations of the garnet-biotite geothermometer. Temperature varies with the calibration and also according to how close to the rim the garnet compositions were measured. Note that diagrams A and B represent garnet crystals from the same rock and that in A temperature apparently decreases from rim to core, whereas the reverse is the case in B.

(Das91 – Dasgupta et al., 1991; FS78 – Ferry and Spear, 1978; HL77 – Hold and Lee, 1977; HS82 – Hodges and Spear, 1982; PL83 – Perchuck and Lavrent'eva, 1983; T76 – Thompson, 1976)



Fig. 3-4.

staurolite zone (e.g., Grambling, 1991; Florence and Spear, 1993; Spear, 1993). Diffusion generally increases Fe/(Fe+Mg) near garnet rims, as originally higher core ratios are reduced by diffusion of Fe outwards.

During retrograde metamorphism, net transfer reactions generally consume newly formed garnet rims and may increase apparent temperatures, whereas generally exchange reactions only re-equilibrate rim compositions and cause a decrease in apparent temperatures. Retrograde metamorphic re-equilibration is likely to have occurred at Hemlo since fluid infiltration modified the peak metamorphic assemblage. This is supported by the presence of chlorite and muscovite crystals oriented obliquely to the regional foliation and epidote overgrowing the mineral assemblage in mafic and calc-silicate rocks, and locally tremolitic rims on hornblende. Incipient chloritization of biotite was noted in three samples, which yielded unreasonably low temperatures. In addition, comparison of Fe/(Fe+Mg) ratios in garnet and biotite yield slopes that are generally sub-parallel, and suggest that, although there is evidence of some disequilibrium, they re-equilibrated during retrograde metamorphism (Fig. 3-5). It is important to note that net transfer reactions and exchange reactions have opposing effects on T estimates, which implies that, locally, peak metamorphic conditions may be recorded (e.g., Spear, 1993). However, this would be fortuitous and, in general, geothermometric data near the deposit are unreliable, which may explain the wide range of temperature estimates proposed in previous metamorphic studies (e.g., Burk et al., 1986; Pan and Fleet, 1993; Kuhns et al., 1994; Powell et al., 1999).

# Figure 3-5.

Fe/(Fe+Mg) ratios for coexisting matrix biotite and garnet rims (used for geothermometry). Although, temperatures calculated from these data vary by  $\sim$ 150°C, there is a relatively consistent relationship between the ratios for biotite and that for garnet, suggesting that these minerals were generally in equilibrium.



Fig. 3-5.

Figure 3-6.

Compositional variations across garnet, represented by almandine (solid), pyrope (dotted), grossular (dash-dot) and spessartine (dark dash-double dot).



Fig. 3-6.

An interesting feature of garnet occurring near the deposit is the high proportion of  $X_{spes}$  (up to ~18%) and reverse zoning (Fig. 3-6). We infer that Mn was partitioned into garnet during the breakdown of chlorite and that the reverse zoning patterns are due to Mn-rich chlorite cores that reacted to form the outer rims of the garnet (cf. Kretz, 1973). This implies that the high  $X_{spes}$  values near the deposit may be related to the effects of pre-peak metamorphic chloritic alteration that subsequently formed garnet.

In summary, peak metamorphic temperatures are interpreted to have reached  $\sim$ 630°C, which is consistent with the mineral assemblages of metapelites (biotite-garnet-staurolite-kyanite/sillimanite) and metabasites (amphibole-plagioclase) in the Hemlo area.

## Pressure

Peak metamorphic pressures were calculated for both metabasites and metapelites. TWQ calculations for garnet-amphibole-plagioclase-bearing metabasites yielded acceptable intersections on only three samples, with pressures between ~5 and 7 kb (Table 3-3b). Reliable pressure estimates for metabasites generally require that garnet is part of the mineral assemblage as this mineral is more sensitive to changes in pressure than other minerals commonly present in these rocks at amphibolite-facies conditions. However, as noted earlier, garnet is either absent, or frequently related to fluid infiltration zones, which probably explains the poor TWQ intersection calculated for most samples.

Estimates of pressure using GASP, GPMB and TWQ calculations on metapelite assemblages also generally range between ~5 and 7 kb, but include outliers at 3 and 8 kb (Table 3-4). This wide range of pressure estimates suggests that peak conditions were only locally preserved. A particular problem with the GASP and GPMB geobarometers is that they rely on  $X_{gros}$  in garnet. However, calcium is generally thought to diffuse at slower rates in garnet than Fe and Mg (e.g., Spear, 1993), which implies that equilibria representing peak metamorphic conditions are unlikely to be preserved, and may explain the wide range of pressures estimated in this and previous studies (e.g., Burk et al., 1986; Pan and Fleet, 1992). An additional problem is that 'peak' pressures are calculated for peak temperature conditions and are thus usually lower than the P<sub>max</sub> (which generally occurs earlier; Spear, 1993).

In summary, our best estimate for the pressure at the thermal peak of metamorphism is ~5 to 7 kb. However, we note that this estimate has a large associated error due to the intrinsic limitations of geobarometry (e.g., Essene, 1982; Kohn and Spear, 1989), problems of disequilibrium and a paucity of suitable samples.

# Discussion

## Timing relationships

Hemlo rocks have been dated by a variety of methods in order to provide a framework in which to reconstruct the pre- to post-peak metamorphic history of the deposit area, and constrain the timing of Au mineralization. These age relationships are summarized in Figure 3-7.

Figure 3-7.

Graphic presentation of geochronological data and inferred timing relationships of sedimentation, igneous intrusive activity, peak metamorphism, retrograde metamorphism, mineralization and remobilization. Deformational episodes are generally constrained indirectly from textural observations of fabric with respect to a dated intrusion (see text for details).

Abbreviations: P – Pukaskwa batholith, CLP – Cedar Lake pluton, CCS – Cedar Creek stock, HBP – Heron Bay pluton, GLP – Gowan Lake pluton.

References: 1 – Corfu and Muir (1989a), 2 – Davis and Lin (2002), 3 – Muir and Elliot (1987), 4 – Kuhns et al. (1994), 5 – Muir (1997), 6 – Beakhouse (2002), 7 – Muir (2002), 8 – Jackson (1998), 9 – Davis (1998), 10 – Stein et al. (2000), 11 – Grant (1995), 12 – Corfu and Muir (1989b).



Fig. 3-7.

#### Peak metamorphism

The timing of peak metamorphism can be broadly constrained by the ages of felsic intrusions, as igneous activity spanned the interval from pre- to post-tectonism (D2) (e.g., Beakhouse, 1998, 2001; Muir, 2002). Pre-tectonic felsic plutonism took place at ~2719 Ma, based on U-Pb ages of the Pukaskwa batholith, which is generally considered the oldest intrusion in the Hemlo area (Corfu and Muir, 1989a). By contrast, the Heron Bay and Cedar Lake plutons, and the Cedar Creek stock, which are interpreted to be syn-tectonic (syn-D2; e.g., Muir and Elliot, 1987; Kuhns et al., 1994; Muir, 1997), have been dated at ~2690-2680 (Corfu and Muir, 1989a, Davis and Lin, 2003). Post-tectonic felsic plutonism (post-D2) is tentatively represented by the Gowan Lake pluton, dated at 2678 (±2) Ma (Beakhouse, 1998; Muir, 2002), but timing relationships are less clear than for the pre- to syn-tectonic plutons. Sillimanite, which arguably is the mineral that was associated with the highest temperatures at Hemlo, is oriented in S2 and S3 strain environments (e.g., Muir and Elliot, 1987), suggesting that peak metamorphism occurred late during D2 or during D3. This indicates that peak metamorphism coincided roughly with the intrusion of the Gowan Lake Pluton (2678  $(\pm 2)$  Ma).

Peak metamorphism has also been interpreted on the basis of U-Pb titanite ages (which are generally younger than those for zircon from the same rocks) as having occurred at 2678-2676 Ma (Corfu and Muir, 1989b) and ~2675 Ma (Jackson, 1998). These estimates were subsequently rejected by Muir (2002) on the grounds that they show a regional trend and might be the product of alteration. He proposed instead (from the ages of plutons classified as syn-tectonic on the basis of emplacement depth)

that metamorphism reached a thermal peak at ~2684 Ma and that the area was at amphibolite-facies conditions from ~2690 to 2675. However, sedimentary zircons have been dated at ~2685 and ~2691 Ma (e.g., Davis, 1998; Davis and Lin, 2003), which implies that either these data are wrong, or the peak of metamorphism was much later than interpreted by Muir (2002).

# Mineralization

Gold mineralization has been interpreted to have occurred between 2685 and 2677 Ma (Davis, 1998), 2694 and 2677 Ma (Muir, 2002), and 2680 and 2677 Ma (Davis and Lin, 2003). The upper bracket (2677 Ma) corresponds to the age of an unaltered feldspar porphyry dyke that cuts mineralization, whereas the lower bracket represents the age of the youngest zircons in wallrock sediments (Davis, 1998), and felsic volcanics of the Moose Lake porphyry (Muir, 2002), or is based on structural interpretations involving the relative timing of gold deposition (interpreted to be syn-D2) and emplacement of the Cedar Lake pluton (pre- or early syn-D2; Davis and Lin, 2003). A syn-D2 timing for mineralization (e.g., Burk et al., 1986; Davis and Lin, 2003) would imply that mineralization occurred during prograde metamorphic heating. Stein et al. (2000) dated the mineralization directly by obtaining Re-Os ages for molybdenite. However, their proposed age of 2670  $\pm$  17 Ma is too young and too imprecise to provide further insights on timing relationships.

#### Remobilization events

Primary gold mineralization was remobilized at least twice during retrograde metamorphism, once at temperatures close to those of peak metamorphism by a sulfide melt, that crystallized progressively during retrograde cooling, and again at ~400°C during calc-silicate alteration (Williams-Jones et al., 1998; Tomkins et al., 2003; Heiligmann et al. 2003). The sulfide melt was dominated by Sb, As and S (with minor Cu, Pb, Hg and Au) (Heiligmann et al., 2003), a system that crystallizes an immiscible Sb-S dominated melt at temperatures below ~550°C (Craig et al., 1974). This is consistent with petrographic observations that indicate an important Au-Sb association in the deposit, expressed by intergrowth of native gold and stibnite (Williams-Jones et al., 1998). If, as proposed above, peak metamorphism reached ~630°C, and occurred at ~2678-2675 Ma, then the deposit cooled to ~550°C at ~2660 Ma, assuming an average cooling rate of ~5°C m.y. (3-7 °C based on blocking temperatures for different isotopic systems; Grant, 1995; Williams-Jones et al., 1998). The final melt in the Sb-As-S system was dominated by As and S and crystallized realgar and orpiment at a temperature of ~300°C (Heiligmann et al., 2003), thereby explaining the observed intergrowth of native gold with realgar in the deposit (Williams-Jones et al., 1998). By coincidence, the upper thermal stability of realgar (~310°C) coincides with the closure temperature of <sup>40</sup>Ar-<sup>39</sup>Ar in biotite (~310°C, Harrison et al., 1985), suggesting that the biotite  ${}^{40}$ Ar- ${}^{39}$ Ar age of 2600 ± 10 Ma (Grant, 1995) marked the end of gold remobilization.

The Au-Ca event is interpreted to have occurred at ~400-450°C, based on mineral equilibria, and is similar to the closure temperature for rutile (~425°C), which

yielded U-Pb ages of 2650 to 2630 Ma for samples of metasediments and felsic dykes (Corfu and Muir, 1989a,b). These data suggest that the formation of the Hemlo gold deposit and subsequent remobilization occurred over a period of ~80 million years.

#### Index mineral distribution

Metamorphic index minerals have commonly been used to establish timing relationships or to constrain P-T paths. However, several generations of porphyroblasts (e.g., aluminosilicates, and possibly two generations of garnet and staurolite) are present locally in the deposit area (e.g., Burk et al., 1986; Pan and Fleet, 1992; 1995; Kuhns et al., 1994; Muir, 1997, Williams-Jones et al., 1998; Powell et al., 1999), and their timing relative to deformational episodes and mineralization are not easy to decipher.

The nature and timing of the aluminosilicates (andalusite?, kyanite, sillimanite) have been particularly controversial, and have been used to support arguments for one (Powell et al., 1999) and two prograde metamorphic episodes (Pan and Fleet, 1995). The former study also argued that intergrowth of ore and ore-related minerals with aluminosilicates indicates a pre-metamorphic timing for mineralization, which contrasts with the pre-peak metamorphic timing that has frequently been proposed (e.g., Kuhns et al., 1994; Muir, 1997; Williams-Jones et al., 1998).

Kyanite and sillimanite are both abundant in the wallrocks, and sillimanite has been observed parallel to S2 and S3 (Elliot and Muir, 1987) or as randomly oriented crystals (post-S2?) (e.g., Powell et al., 1999), suggesting that the thermal peak of metamorphism occurred during D2 or D3 deformational events. An important

question that is unresolved, however, is whether these rocks also contain andalusite. Several studies have inferred or reported the occurrence of andalusite at Hemlo. For example, 'retrograded porphyroblasts of andalusite' were described by Muir (1997, 2002), but petrographic examination has revealed that these porphyroblasts have been entirely replaced by quartz-feldspar-muscovite (Muir, 1997; Williams-Jones et al., 1998) and thus their origin is uncertain. Kuhns et al. (1994) reported the occurrence of rare, unaltered, idioblastic andalusite in the mafic fragmental unit, and this was used by Powell et al. (1999) to constrain P-T relationships. However, Powell et al. (1999) did not find andalusite in this unit, and careful petrographic analysis during this study also failed to identify andalusite. This suggests that its distribution must be extremely limited.

Powell et al. (1999) also described a second type of andalusite, which they state occurs in veins in feldspathically-altered rocks and replaced kyanite due to a contact metamorphic overprint from the 'Heron Bay-Cedar Lake suite'. However, we have examined samples of the material described by them and disagree that this material (1) contains andalusite that replaced kyanite, (2) represents veins in feldspathically altered rocks, or (3) is related to the intrusion of the 'Heron Bay-Cedar Lake suite'. On the contrary, X-ray diffraction analyses of the kyanite-'andalusite' intergrowths indicate that, although the 'andalusite' may have originally been andalusite, it is now kyanite, i.e., andalusite did not replace kyanite.

The kyanite-'andalusite' intergrowths are relatively common where the edge of the sulfidation halo locally overprints low (Fe+Mg), 'high-Al' metapelitic sediments in the hangingwall, which evolved metamorphic index minerals in the order andalusite/kyanite, followed by staurolite, garnet, biotite, kyanite, and sillimanite. In these rocks, early kyanite was preserved, as Fe was partitioned preferentially into sulfides, and staurolite and garnet formation was inhibited (Heiligmann et al., Chapter 2). As this kyanite is hosted by weakly altered and mineralized metapelites, it is locally intergrown with sulfide minerals (cf. Harris, 1989), which suggests that mineralization/alteration occurred prior to peak metamorphism, but does not imply a pre-metamorphic origin for the deposit (e.g., Powell et al., 1999). Feldspathic alteration, which is most commonly associated with the highest gold grade in the core of the deposit, generally does not overprint this unit. In addition, since kyanite-'andalusite'-bearing rocks also contain micas, quartz and feldspars, and grade outwards into biotite-garnet-staurolite-aluminosilicate-bearing metapelites, they are not veins, as suggested by Powell et al. (1999), but partially altered metapelites. Finally, the intrusions of the 'Heron Bay-Cedar Lake suite' have been dated at 2690-2680 Ma and are either pre- or syn-peak metamorphic (Corfu and Muir, 1989a; Davis, 1998; Davis and Lin, 2003). This implies that they could not have been associated with the formation of a late-stage aluminosilicate phase.

The occurrence of both low-(Fe+Mg), 'high-Al' and normal, Barrovian metapelites is also probably the reason that there are different generations of garnet and staurolite. As discussed above, these two types of metapelite evolved index minerals in a different order and at different times during prograde metamorphism. For example, in low-(Fe+Mg), 'high-Al' metapelites near the sulfidation halo, staurolite replaced early kyanite (and is preserved due to weak alteration), whereas in the Barrovian metapelites, staurolite formed later, and ultimately reacted out to form

garnet, biotite and kyanite. Therefore, the two rock types developed different textural relationships among metamorphic index minerals, but their occurrence is not indicative of multiple metamorphic episodes.

# **P-T-t** relationships

Figure 3-8a, b compares our proposed P-T path with those of Burk et al. (1986), Pan and Fleet (1995) and Powell et al. (1999), and estimates of P-T conditions by Kuhns (1988) and Kuhns et al. (1994). Previous studies of Hemlo metamorphism concentrated mostly on wallrocks in the immediate deposit area (e.g., Burk, 1987; Kuhns, 1988; Powell et al., 1999), where diffusion and retrograde re-equilibration likely produced disturbed geothermobarometric data, and their proposed P-T paths consequently underestimated peak metamorphic conditions. Our model calls for rapid burial and concomitant increases in pressure, and slow cooling through exhumation, defining a single path of prograde and retrograde metamorphism. The initial segment of the P-T-t path proposed here, involving a sharp increase of pressure and slower prograde heating, is suggested by the relatively short period of time between sedimentation and peak metamorphism (~10 Ma, see earlier discussion).

During prograde metamorphism, early formation of aluminosilicates is inferred from the occurrence of kyanite-'andalusite' intergrowths (see earlier discussion of index minerals) in wallrocks that fall within the sulfidation envelope around the deposit. Furthermore, the main gold and molybdenite mineralization occurred at ~400-500°C (Heiligmann et al., Chapter 4), and was accompanied by extensive potassic alteration (~2685-2677 Ma).

Figure 3-8a.

1.

Previously proposed P-T estimates for peak metamorphism (Burk = Burk et al., 1986; PF = Pan and Fleet, 1993; K = Kuhns, 1988; K-M2(1994) = Kuhns et al., 1994). Also shown are the P-T loops of Burk et al. (1986) and Powell et al. (1999) and conditions for the formation of their andalusite 1 and 2. Selected equilibrium boundaries for metamorphic reactions are also shown (als – aluminosilicate, and - andalusite, bt biotite, chl – chlorite, kfs – K-feldspar, ky – kyanite, L - liquid, ms – muscovite, pl – plagioclase, prl - pyrophyllite, sil – sillimanite, st – staurolite, qtz – quartz, V - vapor)



Figure 3-8b.

P-T path and relative timing of mineralization and remobilization events. The (dashed) arrow shows the path of crystallization of a Sb-As-S-dominated melt generated during peak metamorphism. An initial, rapid pressure increase is suggested by the relatively short interval between sedimentation and peak metamorphism (~10 Ma) and is followed by drawn out cooling over ~80 Ma.



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Peak metamorphic conditions are indicated by the common occurrence of sillimanite in the metapelites. Since sillimanite is oriented both in S2 and S3 planes (e.g., Muir and Elliot, 1987), the D3 deformational event likely occurred at conditions near those of peak metamorphism (~2678-2675 Ma).

Retrograde metamorphic cooling coincided with progressive crystallization of the sulfide melt, which formed stibnite and gold-bearing quartz veins at temperatures below ~550°C (~2660 Ma) and continued to crystallize until the final melt was dominated by As-S at temperatures below~310°C (2600 Ma). Minerals associated with late-stage, calc-silicate alteration, which are randomly oriented, also formed during retrograde metamorphism, at a temperature of ~400-450°C (~2650-2630 Ma). This analysis of timing relationships indicates that multiple prograde episodes are not necessary to account for the occurrence of metamorphic index minerals in the Hemlo area.

#### Implications of the metamorphic overprint on the Hemlo gold deposit

Most shear zone-hosted or "orogenic" gold deposits occur in greenschist-facies rocks, and are interpreted to have formed after peak metamorphism (e.g., Kerrich, 1993; Groves et al., 1998). The Hemlo gold deposit is a clear exception, as the main mineralization event occurred prior to peak amphibolite-facies metamorphism, and retrograde metamorphic cooling coincided only with remobilization of the ore. These timing relationships are reflected by recrystallized potassically altered rocks hosting primary disseminated gold mineralization, and Au-Sb-As-S mineral associations in veins and fractures that represent post-peak metamorphic remobilization.

The amphibolite-facies metamorphic setting is unusual but by no means unique, as shear zone-hosted mineralization also occurs in metamorphic rocks up to the granulite facies (e.g., Barnicoat et al., 1991). Thus high-grade metamorphic environments are also good potential exploration targets. Recognition of the pre- to syn-peak metamorphic timing of mineralization has important implications for exploration, since mineralization may be remobilized and re-concentrated either as a sulfide melt or by late-stage hydrothermal activity. This is especially pertinent for shear zone-hosted deposits, as the structural settings provide pathways for late-stage hydrothermal fluids. In addition, shear zone-hosted or orogenic gold is commonly associated with elements, such as Sb, As and Hg, that either form minerals with low upper thermal stabilities or are highly soluble in hydrothermal solutions (e.g., stibnite). The characterization of peak thermal conditions therefore has a direct bearing on the interpretation of the remobilization history of the deposit. For example, if peak metamorphic temperatures only reached 500°C (the lower bracket defined by Kuhns et al., 1994) then minerals such as stibnite, zinkenite and berthierite (with upper thermal stabilities of ~556°C, ~545°C, and ~563°C) might still be primary. However, at 630°C these minerals are unstable and therefore must have been remobilized. In fact, more than 25 of the 65 minerals identified at Hemlo by Harris (1989) have upper thermal stabilities below that of peak metamorphism (Heiligmann et al., 2003), and are locally associated with native gold. This implies that pre- to syn-metamorphic gold deposits are therefore favorable environments for telescoped ore zones distal from the original mineralization.

### Conclusions

Geothermobarometric data for metapelites and metabasites indicate that peak metamorphic conditions reached ~630°C and 5-7 kb. However, mineral assemblages in the vicinity of the deposit commonly did not preserve peak metamorphic compositions, as a result of diffusion and post-peak metamorphic re-equilibration. In addition, late-stage fluid infiltration is indicated by the replacement of biotite by chlorite, chlorite aligned obliquely to the foliation of the rocks, epidote overgrowing amphiboles and micas, and late-stage veins of calc-silicate minerals. The enrichment of Mn and reverse zoning in garnet in the vicinity of the deposits suggests a potential chloritic alteration halo around the deposit, which evolved into garnet and biotite during prograde metamorphism. This underlines the difficulty of recognizing metamorphosed alteration zones.

Multiple generations of metamorphic index minerals (such as garnet, staurolite and aluminosilicates) in the Hemlo area are consistent with a single metamorphic cycle of prograde and retrograde metamorphism. The occurrence of these minerals is interpreted to have resulted from (1) the presence of normal ('Barrovian') and 'high-Al, low (Fe+Mg)' metapelites, that crystallize these minerals in a different sequence/order and (2) local sulfidation of 'high-Al, low (Fe+Mg)' metapelites which preserved early, low temperature kyanite by partitioning Fe into pyrite, thereby preventing the normal evolution of these rocks.

The metapelitic mineral assemblages also indicate that peak metamorphism coincided with the formation of sillimanite, which is the mineral associated with the highest temperatures at Hemlo. As sillimanite is aligned in S2 and S3 (e.g., Muir and

Elliot, 1987), peak (thermal) metamorphism likely occurred either during the late-D2 or D3 stage of deformation.

P-T-t relationships at Hemlo indicate that gold mineralization occurred during prograde metamorphism, and was followed by extensive remobilization that started with the formation of a sulfide melt during peak metamorphic conditions. During retrograde metamorphic cooling, this sulfide melt, which was dominated by Sb-As-S, formed an early generation of stibnite (~2660 Ma), and continued to progressively crystallize until the remainder was composed mainly of As-S, and formed realgar and orpiment (~2630 Ma). In addition, gold was remobilized by a volumetrically minor calc-silicate alteration event at ~400°C (2650-2630 Ma). The study indicates thus that gold deposits overprinted by amphibolite-facies and higher metamorphism are potential targets for telescoped mineralization.

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The previous two chapters establish the metamorphic framework of the Hemlo district. Mineralization occurred prior to peak metamorphism, as shown by the recrystallization of ore and alteration assemblages. However, the formation of most metamorphic index minerals in the ore zones was prevented by the strong potassic alteration and the dissolution of sedimentary barite. In addition, sulfidation stabilized pyrite and prevented the formation of Fe-oxides (e.g., magnetite, ilmenite) and Fesulfides (e.g., pyrrhotite).

Chapter IV, constrains physical and chemical conditions of the main mineralization event and explores the genetic origin of the deposit. Equilibria involving K-feldspar, muscovite, barite and pyrite evolved during alteration/mineralization, and are used to thermodynamically model the mineralization event.

# **Chapter IV**

# Mineralogical and thermodynamic constraints on the genesis of the Hemlo Au-Mo deposit, Ontario: an example of a magmatic-related mesothermal deposit?

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#### Abstract

The enigmatic Hemlo gold deposit of north-central Ontario is one of Canada's largest gold producers, containing 95 million tons of ore grading ~8 g/t. Although, the deposit has similarities to other Archean greenstone-hosted gold deposits, including its location in shear zones, formation during regional metamorphism, enrichment in elements such as As, Sb, Hg, W and Te, and lack of base metals such as Cu, it differs from these deposits in several important aspects, notably the extreme enrichment in Mo and K, and the lack of quartz-carbonate veins or primary calc-silicate alteration.

Reconstructing the genesis of the deposit has been complicated by the fact that the mineralization was overprinted by amphibolite-facies metamorphism, which destroyed many primary features (e.g., fluid inclusions), and recrystallized alteration and ore mineral assemblages. However, textural and geochemical considerations such as the disseminated nature of the mineralization, intergrowth of alteration and metamorphic minerals, and the kinetics of the sulfate-sulfide exchange suggest that mineralization occurred during greenschist facies metamorphism at temperatures between 400 and 500°C, and pressures of ~3 to 5 kb. Owing to the relatively short interval between sedimentation and peak metamorphism (10-15 Ma), mineralization likely occurred during prograde metamorphism.

The spatial distribution of ore and ore-related elements (such as Au, Mo, Sb and As) are generally very similar, suggesting strongly that Hemlo formed during a single mineralizing event, and that metamorphic remobilization only locally modified the distribution of ore minerals. These elements, which are all strongly enriched, are hosted mainly by native gold, molybdenite, stibnite and realgar, the last two of which decompose at temperatures below those of peak metamorphism, and must have formed during retrograde cooling.

Ore formation (native gold-molybdenite) involved three important reactions that affected pH,  $fO_2$  and  $fS_2$ , namely, the dissolution of sedimentary barite, the precipitation of pyrite, and the replacement of muscovite by K-feldspar. Ore zone rocks were sulfidized by ore-forming fluids which evolved through dissolution of sedimentary barite and continued to be present during peak metamorphism. During sulfidation, iron was partitioned preferentially into pyrite, which prevented the formation of Fe-bearing metamorphic index minerals (such as garnet and staurolite), oxides (e.g., magnetite, hematite, ilmenite), and low- $fS_2$  sulfides (e.g., pyrrhotite). In addition, alteration strongly enriched the ore zones in potassium (up to 500% by weight), which occurs mainly in K-feldspar (microcline) and muscovite, an assemblage that buffered pH in the ore zones.

Deposition of the native gold-molybdenite assemblage is readily explained by mineral stability and metal speciation considerations, which indicate that these minerals could have precipitated due to the decrease of pH and  $fO_2$  which accompanied potassic alteration and precipitation of pyrite. By contrast, As and Sb are interpreted to have been initially adsorbed onto pyrite growth surfaces, and subsequently released during metamorphic recrystallization.

The thermodynamic and geological constraints indicate that mineralization is most consistent with either modified porphyry or mesothermal mineralization models. In general, porphyry mineralization is interpreted to result from a predominantly magmatic fluid that forms stockworks and veins at relatively shallow crustal levels.

Although, such a fluid at Hemlo would partly explain the ore zone mineral assemblages (K-feldspar and molybdenite), the lack of a genetically associated intrusion, the disseminated nature of the mineralization, the location of the deposit in shear zones, the lack of Cu enrichment, and the depth of emplacement are features that are incompatible with porphyry models. A mesothermal model is favored here, as the unusual features (high K and Mo) can be explained by a mineralizing fluid that contained a significant magmatic component. We therefore propose that Hemlo represents an example of a mesothermal deposit intermediate between magmatic hydrothermal and metamorphogenic orogenic endmembers.

#### Introduction

The origin of structurally-hosted gold mineralization in Archean greenstone belts has long been contentious as is evident from the lack of agreement on their timing (pre-, syn- or post-peak metamorphism) or the origin of the ore fluids (metamorphic, magmatic or meteoritic). However, there is agreement that they represent a single deposit class, as they have similar element enrichment trends, focussed structural control and restricted styles of alteration (Kerrich, 1993). There is also a growing consensus that they formed from fluids produced predominantly by metamorphic devolatilization of large sections of the crust (e.g., Fyfe and Henley, 1973; Witt, 1991; Pettke et al., 1999; Kerrich, 1993; Ridley et al., 1996; Groves et al., 1998; Goldfarb et al., 2001). Similarly, there is a growing consensus that these deposits formed over a 'crustal continuum' (Colvine, 1988; Groves, 1993), during (or closely following) collisional tectonic events (Groves et al., 1998), in rocks metamorphosed at conditions ranging from sub-greenschist to granulite facies conditions.

Although the worldclass Hemlo deposit has several similarities to other Archean greenstone-hosted gold deposits, including its location in shear zones, formation during regional metamorphism, enrichment in elements such as As, Sb, Hg, W and Te, and lack of base metals, such as Cu, it differs from these deposits in several important respects, notably the extreme enrichment in Mo and K, and the lack of quartz-carbonate veins or primary calc-silicate assemblages. This led Groves et al. (2003) to conclude that Hemlo may be incompatible with the orogenic model, and to suggest that it may have formed as a result of multistage epithermal mineralization. Reconstructing the genesis of the Hemlo deposit has been made very difficult by the fact that the mineralization was overprinted by peak, amphibolite facies metamorphism, which destroyed many primary features (e.g., fluid inclusions). As a result, depositional models have generally depended on characteristics such as alteration style, structural setting, or ore mineral associations. However, application of these characteristics has been complicated by the fact that they commonly suggest contradictory interpretations. For example, although pervasive, potassic alteration minerals (such as K-feldspar and muscovite) were recrystallized during amphibolitefacies metamorphism, implying that gold mineralization was pre-peak metamorphic, the presence of minerals such as stibnite, realgar and orpiment, with upper thermal stabilities below that of peak metamorphism, seems to suggest that the mineralization was post-metamorphic.

Early studies of Hemlo favored syngenetic and epithermal models (Patterson, 1984; Goldie, 1985; Valliant and Bradbrook, 1986; Cameron and Hattori, 1985), but porphyry (Walford et al., 1986; Kuhns, 1988), shear-hosted (Burk et al., 1986; Hugon, 1986), and metamorphic replacement models (Philips, 1985) were also proposed. By contrast, recent studies have favored mesothermal-orogenic (e.g., Muir, 1997, 2002), porphyry (e.g., Kuhns et al., 1994; Johnston, 1996), and skarn/late-stage replacement (Pan and Fleet, 1992; 1995) scenarios. A syngenetic exhalative origin (Valliant and Bradbrook, 1986) is compatible with the locally stratiform nature of the Main ore zone, and the spatial association of mineralization with felsic volcanic rocks and layered barite. However, the mineralization is neither stratiform nor stratabound (e.g., Muir, 1997), and a sedimentary exhalative model is incompatible with the extensive

potassic alteration and Au-Mo association (e.g., Williams-Jones et al., 1998). Porphyry models are consistent with the potassic alteration and an abundance of molybdenite, but the absence of any porphyritic intrusion in the area, the strong linear structural control of mineralization, and the absence of copper argue against this type of origin. In addition, calc-silicate assemblages and aluminosilicate-bearing rocks, which have been interpreted to represent propylitic and argillic alteration, respectively (Johnston, 1996), are mainly controlled lithologically and are not alteration-related (Williams-Jones et al., 1998). These inconsistencies with the classic porphyry model, led to the 'modified porphyry model' of Kuhns (1988), which postulated an unexposed pluton at depth from which mineralizing fluids ascended through a shear zone; the term magmatic-hydrothermal may be more appropriate as 'porphyry' implies relatively shallow emplacement, for which there is no evidence.

Mesothermal-orogenic models for Hemlo are consistent with the tectonic setting, syn-metamorphic timing, narrow structural control of mineralization and enrichment of Au, Sb, As, W and Te. However, mesothermal-orogenic deposits generally do not display the extreme enrichment of K (up to 500 %; Bodycomb et al., 2000) and Mo (20 000 tonnes MoS<sub>2</sub> at Golden Giant alone; Kuhns 1988) experienced by the Hemlo deposit. Furthermore, the lack of carbonate and/or albitic alteration (or their metamorphosed equivalents), and the general absence of veins distinguish Hemlo from most mesothermal/shear-hosted deposits (Williams-Jones et al., 1998).

The local occurrence of Au with late-stage calc-silicate alteration has been explained using a skarn/replacement model (Pan and Fleet, 1992; 1995). However this type of alteration is volumetrically minor, and does not account for most of the

gold, which is clearly associated with potassic alteration (e.g., Williams-Jones et al., 1998). In addition, this model invokes a post-peak metamorphic timing for mineralization, which, although consistent with the occurrence of realgar and orpiment, is incompatible with the recrystallized potassic alteration halo. Calc-silicate veins outside the ore zones are unmineralized, and therefore similar veins in the deposit likely reflect simple remobilization of pre-existing gold (Williams-Jones et al., 1998).

At Hemlo, direct evidence for the origin of mineralization, such as fluid inclusions, has been destroyed by metamorphic recrystallization. Nevertheless, fluid characteristics can be constrained indirectly by thermodynamic modeling. Mineral equilibria between ore zones and wallrock lithologies can be used to assess conditions of mineralization (e.g., fluid or rock buffering), constrain parameters such as  $fS_2$ ,  $fO_2$ and pH, and identify mechanisms of Au precipitation. For example, pervasive Kfeldspar and muscovite in the ore zones buffered pH, and  $fS_2$  and  $fO_2$  were controlled by mineral equilibria among sulfur-bearing minerals, the most important of which were barite and pyrite. An important constraint on the mineralizing fluid is that it must be capable of transporting metals that are enriched at Hemlo (e.g., Au, Mo, Sb and As), and that these metals must also precipitate at conditions prevailing in the ore zones.

We have therefore used thermodynamic modeling to evaluate parameters that potentially controlled the gold mineralization at Hemlo, and better understand the genesis of this atypical lode gold system. These data and geological constraints suggest that only modified versions of either magmatic-hydrothermal or mesothermal-

orogenic mineralization models adequately describe the origin of the Hemlo gold deposit.

#### **Geological Setting**

The Hemlo gold deposit is located in the Hemlo-Heron Bay greenstone belt of the Superior province of north-central Ontario in a typical greenstone belt assemblage of intrusive, volcanic and metasedimentary rocks (Fig. 4-1), and contains 95 million tons of ore grading ~8 g/t (Schnieders et al., 2000). Intrusive rocks are mostly granodioritic to tonalitic in composition, whereas extrusive rocks range from felsic to mafic, with the latter dominated by tholeiitic metabasites. Clastic metasedimentary and intermediate to felsic metavolcanic rocks occur throughout the belt, and are composed mainly of meta-greywackes, meta-arenites, marly metasediments, metapelites and intermediate to felsic pyroclastic and epiclastic rocks (cf. Muir, 1997, 2002) (Fig. 4-2). The metamorphic grade of the greenstone belt increases from garnet-chlorite bearing assemblages in the west, to biotite-garnet-sillimanite in the east (Jackson, 1998) In the Hemlo deposit area, regional metamorphism reached amphibolite-facies conditions but, as temperature and pressure variations are within the errors associated with geothermobarometry, no local isograds are detectable (Heiligmann et al., Chapter 3).

#### Stratigraphy and structure

Footwall and hangingwall rocks comprise a series of metasediments including metamorphosed pelites, sandstones, marls and a baritic unit (Fig. 4-3). Corresponding

Figure 4-1.

Simplified geological map of the Heron Bay-Hemlo greenstone belt, showing the location of the Hemlo gold mines (square symbols in box localizing Figure 4-2) and major intrusions (modified from Muir, 1997).





Figure 4-2.

Geological map of the Hemlo area (modified from Muir, 1997), showing the location of mines and distribution of mineralization (black). Note that the Lake Superior shear zone (LSSZ) and Moose Lake fault zone (MLFZ) coincide with the Main and Lower ore zones, respectively.





Figure 4-3.

Simplified cross-section through the Golden Giant mine, which is located approximately in the center of the deposit. Mineralization occurs at the contact between footwall metasediments (including wackes, marls and pelites) and quartz-feldspar porphyry rocks (Lower ore zone), and between the quartz-feldspar porphyry and hangingwall metasediments (including wackes, marls and pelites) and the mafic fragmental unit (Main ore zone). Note that the mafic fragmental unit only occurs in the hangingwall, and is less extensive or absent in other parts of the deposit (modified from Sutcliffe, 1988).



Fig. 4-3

units on either side of the deposit have been shown to be geochemically indistinguishable (Bodycomb et al., 2000), and are thought to represent the limbs of a proto-sheath fold (Lin, 2001). The mineralization is hosted predominantly by two steeply dipping sub-parallel ore zones; which coincide with the Lake Superior shear zone and the Moose Lake fault zone (Fig. 4-2). The Lower ore zone is discontinuous and occurs at the contact of footwall metasediments with a quartz-feldspar porphyry unit. By contrast, the Main ore zone is essentially continuous throughout the deposit, and comprises one major and several subordinate tabular horizons, located at or proximal to the contact between hangingwall metasedimentary and quartz-feldspar porphyry or mafic fragmental rocks.

The mineralization is structurally controlled (e.g., Walford et al., 1986; Hugon, 1986; Burk et al., 1986), and Muir (1997) noted that the deposit occurs in zones of competency contrast, between competent quartz-feldspar porphyry, and less competent sedimentary and baritic rocks. The intensity of alteration is related to the degree of deformation (i.e., the most altered rocks are also highly deformed) and lenticular to tabular ore zones are spatially associated with structures that transect stratigraphy. Finally, ore zones have shapes, orientations and distributions that are related to smaller scale structures within the larger-scale deformation structures.

Mineralization was preceded by an early deformation event (D1), recognized by a remnant fold in the vicinity of the deposit, and coincided with or was succeeded by at least two regional episodes of deformation related to sinistral transpression and dextral shearing (D2 and D3). The main fabric in the ore zones is oriented dominantly in S2 and locally in S3 (Muir,1997, 2002; Lin, 2001).

#### Wallrocks and ores

Wallrocks to the ore zones are composed primarily of metasediments (e.g., metapelites, meta-greywackes, meta-arenites, marly sediments) and have been metamorphosed to mid-amphibolite facies (Fig. 4-3). Assemblages indicative of amphibolite conditions include biotite-garnet-staurolite-kyanite/sillimanite in metapelites, and hornblende-plagioclase in marly sediments. Geothermobarometric calculations indicate that peak metamorphism reached temperatures of ~630°C and pressures of 5 to 7 kb (Heiligmann et al., Chapter 3).

The Main and Lower ore zones are separated by a quartz-feldspar porphyry unit that has been interpreted as either entirely intrusive (Kusins et al., 1991; Kuhns et al., 1994; Johnston, 1996) or as an intrusive-extrusive complex (e.g., Muir, 1997; Williams-Jones et al., 1998). This unit consists mainly of quartz, plagioclase, muscovite and microcline, and was foliated and recrystallized during regional metamorphism.

The 'mafic' fragmental unit is a heterogeneous volcanic-sedimentary rock characterized by mainly felsic clasts in a predominantly mafic matrix. This unit is overprinted locally by mineralization and alteration, and has been variably interpreted to be a mafic volcaniclastic (Kuhns, 1988), a mafic conglomerate (Burk et al., 1986), a hydrothermal breccia (Johnston, 1996), a biotitized felsic fragmental (Lin, 2001), or a Temiskaming-type mafic conglomeratic deposit (Heiligmann et al., Chapter 2). Unaltered segments of this unit contain amphibole, plagioclase, muscovite and quartz, and minor magnetite, garnet, epidote and pyrrhotite. In altered rocks, amphibole,

garnet, magnetite and pyrrhotite were replaced by biotite, muscovite, microcline and pyrite (e.g., Heiligmann et al., Chapter 2).

Ore zone rocks include three main subunits (baritic, feldspathic, muscovitic) that reflect altered and mineralized equivalents of the metasedimentary, 'mafic' fragmental, and to a lesser extent the quartz-feldspar porphyry rocks (Williams-Jones et al., 1998). The only primary ore zone lithology is the barite-rich rock that occurs at the contact between the clastic metasedimentary and quartz-feldspar porphyry units in both the Main and Lower ore zones. Barite-rich rocks have been variably interpreted to be sedimentary (Cameron and Hattori, 1985; Valliant and Bradbrook, 1986; Burk, 1987; Kuhns, 1988; Thode et al., 1991), or hydrothermal in origin (Harris, 1989; Johnston, 1996; Muir, 2002). However, sedimentary barite occurs outside the ore zones in stratigraphically similar horizons, and has the same S and Sr isotopic signatures (Cameron and Hattori, 1985), suggesting deposition in a restricted sedimentary basin. Some barite is clearly hosted by veinlets and breccias, but these occurrences can be explained by remobilization during hydrothermal and metamorphic events. Barite-rich ore consists of massive to semi-massive barite with interlayers or fragments of feldspathic and/or muscovitic material. This subunit is characterized by quartz, barite, microcline and pyrite, with lesser muscovite, plagioclase and biotite, and traces of calcite, chlorite and titanite.

Feldspathic ore generally forms fine-grained, granoblastic rocks composed of barian microcline, quartz, pyrite and Ba- and V-muscovite, with minor to trace amounts of barite, plagioclase, biotite, calcite, titanite, rutile and tourmaline. This ore

type exhibits significant textural and compositional heterogeneity, including mica- and quartz-rich layers, and variable pyrite concentrations.

Muscovitic ore is characterized by recrystallized, well-foliated and/or granoblastic quartz-muscovite-microcline schists, with locally abundant pyrite, and minor to trace amounts of barite, biotite, tourmaline, calcite, titanite, rutile and apatite. Ore mineral assemblages are complex, and include (in addition to native gold) pyrite, molybdenite, stibnite, realgar, sphalerite, zinkenite and tetrahedrite-tennantite (Harris, 1989). An additional subunit, biotitic ore, occurs locally where ore zones overprint the 'mafic' fragmental unit; biotitic ore is dominated by quartz, microcline and biotite, with subordinate barite, pyrite, muscovite and plagioclase.

#### Alteration

The ore zones are strongly enriched in potassium (up to 500%, Bodycomb et al., 2000), which occurs mainly in K-feldspar (microcline) and muscovite. Microclinization predominates in the center of the ore zones, and is associated with the highest average gold grades. Microcline contains significant BaO (up to 27%; Williams-Jones et al., 1998), indicating substitution of barium during mineralization and/or metamorphism. Grading outwards from this central zone, the abundance of muscovite increases, to the point where it is the most important potassium-bearing mineral. Locally, muscovite contains vanadium and barium (up to 8 wt %; Bodycomb et al., 2000), again indicating substitution during mineralization and/or metamorphism. The outward zonation of K-feldspar and muscovite halos reflects decreasing intensity of potassic alteration, which locally extends for up to 30 m into the hangingwall

(Williams-Jones et al., 1998; Heiligmann et al., Chapter 2). During peak metamorphism, muscovite was recrystallized, and now defines S2 and S3 schistosities (Muir, 1997; 2002); microcline forms granoblastic annealed textures, and grain boundaries are characterized by triple junctions.

Biotitic alteration occurs locally in altered and mineralized 'mafic' fragmental rocks, where biotite replaced amphibole, and was a product of sulfidation and potassic alteration of this lithology (Heiligmann et al., Chapter 2). Biotite and amphibole commonly define the main rock fabric, indicating that both minerals were re-oriented during the principal deformational event.

Volumetrically minor calc-silicate alteration occurs in the ore zones and includes calcite, grossular garnet, diopside and titanite (cf. Pan and Fleet, 1992, 1995). These minerals are related predominantly to veins, and are generally oriented randomly, indicating formation after deformation and peak metamorphism (e.g., Williams-Jones et al., 1998).

Ore zone rocks were sulfidized by ore-forming fluids, which evolved through dissolution of barite, and continued to be present during peak metamorphism. During sulfidation, iron was partitioned preferentially into pyrite, which prevented the formation of Fe-bearing metamorphic index minerals (such as garnet and staurolite), oxides (e.g., magnetite, hematite, ilmenite), and low- $fS_2$  sulfides (e.g., pyrrhotite). These Fe-bearing minerals occur in wallrocks, but disappear within the alteration envelope (Heiligmann et al., Chapter 2). Biotite, although present in both country and ore zone rocks, lost Fe within the sulfidation halo, where it is typically of phlogopitic composition. Depletion of Fe in silicates and oxides, and the persistence of pyrite

through peak amphibolite-facies metamorphism, indicate that  $fS_2$  levels remained relatively high during metamorphism (Heiligmann et al., Chapter 2).

#### Timing of mineralization with respect to metamorphism

Gold mineralization is generally interpreted to have occurred prior to or synpeak metamorphism. This interpretation is based largely on structural relationships between mineralization and deformation, U-Pb geochronology, and the observation that potassic alteration minerals have been completely recrystallized by metamorphism (Muir, 1997; 2002; Williams-Jones et al., 1998; Powell et al., 1999; Lin, 2001; Davis and Lin, 2003; Heiligmann et al., Chapter 3). The relatively early timing contrasts with previous suggestions of a post-peak metamorphic origin, which were based mainly on the local association of gold with late-stage calc-silicate alteration (e.g., Pan and Fleet, 1995), and the occurrence of low temperature sulfide minerals (Harris, 1989). However, calc-silicate alteration is volumetrically minor, and accounts only for a minor proportion of the mineralization (Williams-Jones et al., 1998; Muir, 2002), and minerals such as realgar, stibnite and zinkenite formed as a result of late-stage remobilization of As, Sb and Pb by hydrothermal fluids (Kuhns et al., 1994), exsolution (Powell and Pattison, 1997), or a sulfide melt (Tomkins et al., 2003, 2004; Heiligmann et al., 2003).

The genetic model of Williams-Jones et al. (1998) and Heiligmann et al. (2003) proposed a pre-peak metamorphic Au-Mo mineralization event associated with potassic alteration. Near peak metamorphic conditions, some gold and ore-related elements (Sb, As, Pb, Hg) are interpreted to have formed a sulfide melt, which
crystallized progressively during retrograde cooling (Heiligmann et al., 2003). The early immiscible melt in the system Sb-As-S crystallized stibnite and native gold, minerals which are frequently observed in fractures or low pressure zones (Michibayashi, 1995). Crystallization continued until the final melt was dominated by As-S, and saturated with minerals such as realgar and orpiment at temperatures below ~300°C (Heiligmann et al., 2003). In addition, late-stage calc-silicate alteration locally remobilized gold during retrograde metamorphism. Mineral equilibria (e.g., zoisite, garnet, anorthosite) and fluid inclusion data indicate that this alteration occurred at ~400 to 500°C (Pan and Fleet, 1992; Heiligmann et al., Chapter 2).

# Conditions of alteration and mineralization

## **Constraints on mineralization**

#### The significance of barite and pyrite

The Main and Lower ore zones coincide with baritic sediments or contain significant concentrations of barium substituted in K-feldspar (up to 17 wt%) and micas (up to 8.2 wt %) (Williams-Jones et al., 1998). Although the correlation coefficient between Au and Ba is low , ~0.29, economic gold concentrations are associated with elevated levels of barium (Fig. 4-4). Therefore, barite did not 'dilute' the mineralization as suggested by Kuhns (1988) and Johnston (1996), but is an integral part of the ore zones. Lin (2001) interpreted baritic sediments to be the main precursor lithology for mineralization. However, bulk rock geochemical data indicate that the precursors were primarily metasediments similar to those found in the

Figure 4-4.

Distribution of Au and Ba concentrations in altered and gold-mineralized rocks at Hemlo. Although the correlation coefficient is low (0.29), rocks with high Ba concentrations are generally associated with high gold grades (data from Williams-Jones et al., 1998).



Fig. 4-4

wallrocks (e.g., wackes, pelites, marls), and to a lesser extent, mafic fragmental and quartz-feldspar porphyry rocks (Bodycomb et al., 2000).

The Ba enrichment of recrystallized K-feldspar and micas indicates that barite was partially remobilized during mineralization and/or metamorphism. This is consistent with S and Sr isotopic data, which show that barite and pyrite exchanged sulfur during mineralization (Cameron and Hattori, 1985) and peak metamorphism (Thode et al., 1991). However, the lack of low-pH alteration assemblages (or their metamorphosed equivalents) indicates that  $fS_2$  conditions in the mineralizing fluid never reached extreme levels such as those associated with high-sulfidation epithermal mineralization. On the other hand, the dissolution of barite led to the preferential partitioning of Fe from oxides and silicates into pyrite. Therefore, the abundance of pyrite in the ore zones is not only related to the composition of the mineralizing/alteration fluid but also to the presence of Fe in the precursor lithologies. This explains why the abundance of pyrite at Hemlo does not correlate positively with high gold grades (Cameron and Hattori, 1985).

#### Evidence for pene-contemporaneous concentrations of ore-related elements

The ore zones are strongly enriched in Au, Mo, Sb and As, and to a lesser extent in Pb, Hg, W, V, Tl and Te (Bodycomb et al., 2000). Based on lithogeochemical evidence, Williams-Jones et al. (1998) suggested that these elements concentrated in a single mineralizing event, which is consistent with the distribution and abundance of Au, Mo, As and Sb in the ore zones (Fig. 4-5). Multiple mineralizing events are unlikely to have produced the same spatial distribution of Figure 4-5.

Distribution of Au (black, solid), Mo (grey, solid), Sb (black, broken line) and As (black, dotted) in a section across the Hemlo deposit. The coincidence of peak concentrations of these elements suggests that they were all introduced during the main mineralization event (Drill hole 440NQ-34 Golden Giant mine; data from Williams-Jones et al., 1998).



Fig. 4-5

these elements, and thus the superposition of their peak concentrations is taken to indicate that these four elements were concentrated pene-contemporaneously. Subsequent, post-peak metamorphic remobilization locally modified the distribution of these elements within the ore zones, as shown by their concentration in low pressure zones such as quartz veins and fault hinges. It is noteworthy that the average copper content of ore zone rocks is ~33 ppm, which is similar to its concentration in the unaltered sedimentary wallrocks (31 ppm, Williams-Jones et al., 1998). This indicates that copper was not added during mineralization (Williams-Jones et al., 1998).

## Temperature-pressure constraints on mineralization

The temperature of the main Au-Mo mineralization event cannot be determined unequivocally, but textural evidence and geochemical considerations can be used to bracket a range of possible temperatures. Barite and pyrite are the main repositories of sulfur in the ore zones, and exchanged sulfur isotopes during mineralization (Cameron and Hattori, 1985; Thode et al., 1991). As sulfate-sulfide exchange, for kinetic reasons, only takes place at temperatures above ~250 °C (Benning and Seward, 1996; Ohmoto and Lasaga, 1982), the latter represents a lower limit for the temperature of mineralization at Hemlo.

In Barrovian-series metamorphic rocks, the first amphibole to appear is actinolite, which forms at greenschist facies conditions (Spear, 1993). At Hemlo, amphibole in the mafic fragmental unit was replaced by the alteration mineral biotite, which suggests that mineralization occurred at P-T conditions equivalent to at least those of the greenschist facies (Heiligmann et al., Chapter 3). Similarly, the local presence in the metapelitic wallrocks of staurolite containing inclusions of pyrite indicates that mineralization occurred prior to the attainment of amphibolite-facies conditions (Fig. 4-6). This implies that mineralization did not occur near peak metamorphic conditions (~630°C, 5-7 kb; Heiligmann et al., Chapter 3), as staurolite either reacts out or only persists metastably at these conditions. An additional constraint on temperature-pressure conditions is the lack of quartz veins associated with Au-Mo mineralization. As stated above, the bulk of the mineralization occurs as disseminated Hg- and Ag-bearing native gold in potassically altered rocks, and is associated primarily with molybdenite. Mineralized quartz veins occur locally in the deposit, but do not account for the bulk of the ore. Importantly, these quartz veins generally do not contain any molybdenite, and if gold is present, it is invariably associated with low temperature sulfides (such as stibnite and realgar), and therefore is interpreted to represent late-stage remobilization (Kuhns et al., 1994; Powell and Pattison., 1997; Tomkins et al., 2003, 2004; Heiligmann et al., 2003). Disseminated mineralization occurs commonly in relatively hot ductile rocks, whereas in brittle regimes, gold is generally hosted by veins or stockworks. Disseminated mineralization is also found in high-sulfidation epithermal and Carlin-type environments, in which dissolution of the host rocks by acidic fluids (weakly acidic in the case of the carbonate-hosted Carlin deposits) increases the porosity. However, alteration assemblages at Hemlo are inconsistent with significant H<sup>+</sup> metasomatism, and carbonate-bearing lithologies are absent. This suggests that the predominantly disseminated mineralization formed in relatively hot and ductile rocks (i.e., near the

Figure 4-6.

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Photomicrograph of staurolite with pyrite inclusion in metapelite adjacent the ore zones. The distribution of pyrite inclusions at the edge of the staurolite crystal suggests that sulfidation of these metapelites occurred during the formation of staurolite.





brittle-ductile transition). We therefore conclude from the above discussion that mineralization probably occurred during greenschist facies metamorphism at temperatures between 400 and 500 °C, and pressures of ~3 to 5 kb.

# Thermodynamic modeling

For the purpose of thermodynamic modeling, we have assumed that gold mineralization at Hemlo occurred at a temperature of 450°C and a pressure of 4 kb, was associated with potassic alteration, and involved interaction with sedimentary barite. The mineralizing fluid was rich in Au, Mo, Sb and As, and precipitated these elements during a single mineralization event. Furthermore, both fluid and rock buffering occurred in the ore zones. Pervasive potassic alteration added K, Fe and Si to the rocks and depleted them in Ca, Mg and Na (Williams-Jones et al., 1998, Bodycomb et al., 2000), but also dissolved significant concentrations of barite, which increased  $fS_2$  and substituted Ba into alteration minerals such as K-feldspar and micas.

# Ore zone buffering

Three important reactions record conditions in the ore zones, namely, the dissolution of barite, the precipitation of pyrite, and the replacement of muscovite by K-feldspar. Barite is present in all mineralized rocks at Hemlo, either as massive bodies or disseminated grains, and Ba is widely substituted into silicate minerals. The dissociation of barite can be expressed by the reaction:

$$BaSO_4 = Ba^{2^+} + SO_4^{2^-}$$
(1)

Since the only significant Fe-bearing sulfide in the ore zones is pyrite, and  $H_2S$  generally is the predominant sulfur-bearing species in the pyrite stability field, the transition from sulfate to sulfide can be expressed by the reaction:

$$SO_4^{2-} + 2H^+ = H_2S + 2O_2$$
 (2)

Combining (1) and (2), the reaction becomes:

<u>.</u>

$$BaSO_4 + 2H^+ = Ba^{2+} + H_2S + 2O_2$$
(3)

This reaction describes the dissolution of barite within the pyrite stability field, and indicates that the dissolution was dependent on both pH and total sulfur activity.

Iron enrichment in the ore zone rocks and the presence of pyrite as the only volumetrically important Fe-bearing mineral indicate that available iron was partitioned preferentially into pyrite by a reaction such as:

$$Fe^{2+} + 2H_2S + 0.5O_2 = FeS_2 + 2H^+ + H_2O$$
 (4)

where  $Fe^{2+}$  represents an iron-bearing silicate mineral. This is supported by the lower iron contents of ferromagnesian silicates such as biotite in mineralized rocks relative to the wallrocks, and the fact that Fe-bearing metamorphic minerals such as staurolite and garnet are absent in the ore zones (Heiligmann et al., Chapter 2). In addition, the isotopic compositions of barite and pyrite suggest that some of the sulfur from barite precipitated as pyrite during mineralization and metamorphism (Thode et al., 1991).

The pH of the mineralizing fluid was controlled by the K-feldspar-muscovite reaction which can be expressed as:

$$0.5KAl_3Si_3O_{10}(OH)_2 + 3SiO_2 + K^+ = 1.5KAlSi_3O_8 + H^+$$
(5)

This reaction served to control the pH of the ore fluid during potassic alteration. Additional, barian feldspar formed by the dissolution of barite, which can be expressed by combining reactions 3 and 5:

$$BaSO_{4} + 2KAl_{3}Si_{3}O_{10}(OH)_{2} + 8SiO_{2} + 2K^{+} =$$
  
$$4KAlSi_{3}O_{8} + BaAl_{2}Si_{2}O_{8} + H_{2}S + 2O_{2} + 2H^{+}$$
(6)

Note that the barian feldspar at Hemlo is hyalophane  $[(Ba,K)AlSi_3O_8]$ , which is the intermediate phase in the solid solution series between K-feldspar and celsian  $(BaAl_2Si_2O_8)$ .

The reactions presented above (reactions 1-5) represent a system with 6 mobile components, of which three need to be fixed for the system to be defined. This implies that if  $aK^+$ ,  $aBa^{2+}$  and total sulfur are fixed, the other parameters can be determined. However, the value for  $aK^+$  cannot be measured directly and needs to be assumed. Since the potassic alteration at Hemlo is comparable to that of porphyry gold systems, a value for  $aK^+$  of 0.5 (commonly used for modeling such systems; e.g., Barnes, 1979), was adopted for our calculations. This value yields a pH of ~4.5, which is near neutral (neutral pH = 4.56, at 400°C and 4 kb) and is consistent with the alteration assemblages at Hemlo (i.e., the lack of H<sup>+</sup> metasomatism).

Barium activity can be approximated by recasting reaction 6 in terms of pH and  $aBa^{2+}$ :

$$KAl_3Si_3O_{10}(OH)_2 + 2SiO_2 + Ba^{2+} = KAlSi_3O_8 + BaAl_2Si_2O_8 + 2H^{4+}$$

This reaction is independent of  $fO_2$  and has to occur at the same pH conditions as the K-feldspar-muscovite buffer. Thus, at a pH of ~4.5, barium activity is ~0.005.

The total sulfur activity was estimated from the stability fields of selected sulfide and oxide minerals determined as a function of total sulfur ( $\Sigma aS$ ) and log  $fO_2$  (Fig. 4-7). Ore zone conditions were estimated from the equilibrium boundary for the following reaction involving biotite, pyrite and K-feldspar:

$$KFe_3AlSi_3O_{10}(OH)_2 + 6H_2S + 1.5O_2 = 3FeS_2 + KAlSi_3O_8 + 7H_2O$$
(7)

Activities of biotite and microcline used in the calculations were based on compositional data obtained from electron microprobe analyses, and an assumption of ideal mixing (Table 4-1). The  $\log \Sigma a S$  of the ore fluid is estimated to have been -1 which is within the narrow range of  $\log \Sigma a S$  in which biotite and pyrite co-exist stably (Fig. 4-7). However, it should be noted that biotite in these rocks is a product of peak metamorphism and therefore -1 represents an upper limit for  $\log \Sigma a S$ .

By combining reactions 3 and 4 the equilibrium between sulfate and sulfide at Hemlo can be described by a reaction which is independent of pH but involves oxygen:

$$BaSO_4 + Fe^{2+} + H_2S = Ba^{2+} + FeS_2 + H_2O + 1.5O_2$$
(8)

Given the abundance of barite and pyrite and their intimate spatial relationship in the deposit, we conclude that this reaction controlled  $fO_2$ .

# Transport and precipitation of ore-related metals

The most important elemental enrichments in the ore zones are of Au, Mo, Sb and As (Williams-Jones et al., 1998); ore zone rocks (>1 g/t Au) average ~10 ppm Au, 1050 ppm Mo, 310 ppm Sb and 210 ppm As.

# Figure 4-7.

A plot of  $\log fO_2$  versus  $\log \Sigma aS$  showing the stability field of selected sulfides and oxides at 450°C and 4 kb. Ore zone conditions (shaded grey, indicated by arrow) are bracketed by the stability fields of pyrite and ore zone biotite (dash-dot). This data suggests that ore zone conditions are dominated by relatively high total sulfur of  $\log \Sigma aS$  of -1. Also shown is the barite dissolution equilibria at various  $aBa^{2+}$  conditions.



Fig. 4-7

Reaction	250 °C saturation	250 °C 0.3 kb	<b>450 °C</b> 4 kb	600 °C 5 kb
$H_2S = H^+ + HS^-$	-7.02	-6.90	-7.17	-7.89
$H_2S + 2O_2 = HSO_4 + H^+$	61.97	62.04	37.47	26.01
$H_2S + 2O_2 = SO_4^{2} + 2H^+$	56.71	56.94	31.16	18.59
$HS^{-} + 2O_2 = SO_4^{2-} + H^{+}$	63.73	63. <b>8</b> 3	38.32	26.49
$H_2O = H^{\dagger} + OH^{\dagger}$	11.19	10.98	9.13	8.80
$FeS + H_2S + 0.5O_2 = FeS_2 + H_2O$	22.56	22.59	13.17	8.67
$FeS + HS' + H^+ + 0.5O_2 = FeS_2 + H_2O$	29.59	29.49	20.33	16.56
$Fe_{3}O_{4} + 6HS^{-} + 6H^{+} + O_{2} = 3FeS_{2} + 6H_{2}O$	99.24	98.69	73.32	63.64
$Fe_{3}O_{4} + 3HS^{-} + 3H^{+} = 3FeS + 3H_{2}O + 0.5O_{2}$	10.49	10.23	12.32	13.96
$3 \text{ FeS}_2 + 6\text{H}_2\text{O} + 11\text{O}_2 = \text{Fe}_3\text{O}_4 + 6\text{SO}_4^{2-} + 12\text{H}^+$	283.14	284.32	156.63	95.27
$2Fe_{3}O_{4} + 0.5O_{2} = 3Fe_{2}O_{3}$	17.61	17.61	10.69	7.52
$3\text{FeS}_2 + 6\text{H}_2\text{O} + 11\text{O}_2 = \text{Fe}_3\text{O}_4 + 6\text{HSO}_4^+ + 6\text{H}^+$	314.72	314.95	194.52	139.79
$2\text{FeS}_2 + 4\text{H}_2\text{O} + 7.5\text{O}_2 = \text{Fe}_2\text{O}_3 + 4\text{HSO}_4 + 4\text{H}^+$	215.68	215.84	133.24	95.70
$3FeS + 3H_2O + 0.5O_2 = Fe_3O_4 + 3H_2S$	10.58	10.46	9.19	9.71
$3FeS_2 + 6H_2O = Fe_3O_4 + 6H_2S + O_2$	-57.11	-57.31	-30.30	-16.29
$2FeS_2 + 4H_2O = Fe_2O_3 + 4H_2S + 0.5O_2$	-32.20	-32.34	16.64	8.36
$3\text{FeS}_2 + 6\text{H}_2\text{O} + 11\text{O}_2 = \text{Fe}_3\text{O}_4 + 6\text{HSO}_4^- + 6\text{H}^+$	314.72	314.95	194.52	139.79
$3FeS_2 + 6H_2O = Fe_3O_4 + 6H_2S + O_2$	-57.11	-57.31	-30.30	-16.29
$BaSO_4 + 2H^+ = Ba^{2+} + H_2S + 2O_2$	-67.64	-67.54	-41.49	-29.91
$BaSO_4 + H^+ = Ba^{2+} + HS^- + 2O_2$	-74.66	-74.43	-48.65	-37.80
$1.5 \text{ KAlSi}_{3}\text{O}_{8} + \text{H}^{+} = 0.5 \text{ KAl}_{3}\text{Si}_{3}\text{O}_{10}(\text{OH})_{2} + 3\text{SiO}_{2} + \text{K}^{+}$	3.96	4.00	4.14	4.14
Au (s) + $2H_2S$ + 0.25 O <sub>2</sub> = Au(HS) <sub>2</sub> + H <sup>+</sup> + 0.5H <sub>2</sub> O	1.50	1.54	-2.98	-5.71
Au (s) + 2HS <sup>-</sup> + H <sup>+</sup> + 0.25 O <sub>2</sub> = Au(HS) <sub>2</sub> <sup>-</sup> + 0.5H <sub>2</sub> O	15.55	15.34	11.36	10.07
Au (s) $+ 2SO_4^{2} + 3H^+ = Au(HS)_2^{-} + 3.75O_2 + 0.5H_2O$	111.92	-112.33	-65.29	-42.90
Au (s) + 2HSO <sub>4</sub> + 2H <sup>+</sup> = Au(HS) <sub>2</sub> + 3.75O <sub>2</sub> + 0.5H <sub>2</sub> O	-122.44	-122.54	-77.92	-57.73
$AuCl + Cl = AuCl_2$	1.18	1.15	1.83	2.48
Au (s) + 2Cl' + 0.25 $O_2 + H^+ = AuCl_2^- + 0.5H_2O$	3.16	2.95	3.27	4.30
$AuOH_{(ac)} + H_2O = Au(OH)_2 + H^+$	-13.05	-12.92	-11.21	-10.99
$Au_{(s)} + 0.5H_2O + 0.25O_2 = AuOH_{(an)}$	0.21	0.17	-1.73	-2.62
$HMoO_{4}^{2} = MoO_{4}^{2} + H^{+}$	-6.67	-6.51	-7.46	-8.54
$HMoO_4^{-} + H^{+} + 2H_2S \approx MoS_2 + 3 H_2O + 0.5O_2$	4.67	4.67	2.14	0.58
$HM_0Q_1 + 5H^+ + 2SQ_1^2 = M_0S_2 + 3H_2Q + 4.5Q_2$	-108.74	-109.21	-60.18	-36.61
$MoQ_{*}^{2} + 2HS_{*}^{2} + 4H_{*}^{4} = MoS_{*} + 3H_{*}Q + 0.5Q_{*}$	25.39	24.97	23.93	24.90
$HM_0\Omega_1^{-1} + 3H^+ + 2HS\Omega_1^{-1} = M_0S_1 + 3H_1\Omega_1 + 4.5\Omega_1$	-119.27	-110.42	-77 R1	-51 45
$FeS_2 + As(OH)_2 = FeAsS + H_2S + 0.5H_2O + 1.25O_2$	-47.36	-47.37	-29.21	-20.66
	17.50			

Table 4-1. Reactions and log K's used for the calculations of the pH-log  $fO_2$  diagrams.

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Data for aqueous species from SUPCRIT and following updates (Shock et al. (1997a), Sverjensky et al. (1997),

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Shock et al. (1997b), Haas et al. (1995), Sassani et al. (1998), Shock et al. (1988), Shock et al. (1989))

Aqueous gold complexes from Akinfiev 2001

Mo aqueous complexes from Shock et al. 1997a

Molybdenite, gold, pyrite, pyrrhotite, magnetite, hematite from Robie, 1995

K-feldspar and muscovite from Holland, 1998

H2O, H+ from Unitherm default database

Arsenopyrite from NRH, 1971

Gold in hydrothermal solutions is generally considered to be transported as chloride-, hydroxy or bisulfide complexes (e.g., Gammons and Williams-Jones, 1997; Seward and Benning, 1996; Stefansson and Seward, 2004). Chloride complexes dominate at high temperatures and salinities and at low pH, whereas bisulfide species predominate at lower temperatures. Hydroxy complexes such as Au(OH)<sup>-</sup> have been proposed for intermediate to high (~500°C) temperatures (Zotov et al., 1985; Gammons and Williams-Jones, 1997; Stefansson and Seward, 2004); but there is a lack of data for elevated pressures. Gold solubility calculations for ~450°C indicate that the predominant species in the pyrite stability field near the K-feldspar-muscovite buffer is the bisulfide complex, Au(HS)<sub>2</sub><sup>-</sup> (Fig. 4-8), whereas chloride complexes dominate only at very acid conditions.

Experimental data for molybdenum transport are sparse, but oxyacid complexes such as  $MoO_4^{2-}$ ,  $HMoO_4^{-}$  or  $H_2MoO_4$  are interpreted to predominate under geological conditions (Wood et al., 1987). Solubility calculations using the UNITHERM computer program (Shvarov, 1999; Shvarov and Bastrakov, 1999) indicate that, at pH values between 1 and 7.4, the dominant Mo species at Hemlo is  $HMoO_4^{-}$ ; the solubility contours are sub-parallel to those of Au(HS)<sub>2</sub><sup>-</sup> (Fig. 4-8).

Transport of antimony in most hydrothermal fluids is dominated by either hydroxy species such as  $Sb(OH)_3$  (Wood et al., 1987; Shikina and Zotov, 1999; Zotov et al., 2003), or sulfide complexes such as  $HSb_2S_4^-$  and  $Sb_2S_2(OH)_2$  (Krupp, 1988; Spycher and Reed, 1989; Akinfiev et al, 1993). In general,  $HSb_2S_4^-$  dominates at intermediate pH, whereas  $Sb_2S_2(OH)_2$  is more important at lower pH (Krupp, 1988). Chloride

## Figure 4-8.

 $Log O_2 - pH$  diagram showing solubility contours for Au and Mo and phase relationships in the Fe-O-S system at conditions interpreted for mineralization. The stability boundary between muscovite and K-feldspar and the saturation boundary of barite are also shown. The solid circle shows the inferred conditions of the ore fluid prior to mineralization, and the arrow the proposed evolutionary path of the fluid. Au(HS)<sub>2</sub><sup>-</sup> and HmoO<sub>4</sub><sup>-</sup> may saturate near the K-feldspar-muscovite buffer and barite dissolution curves. Note that arsenopyrite is very soluble in the pyrite stability field and therefore unlikely to precipitate. At high chlorinity, AuCl<sup>-</sup> becomes the predominant Au species, which could lead to the precipitation of gold and molybdenite by an increase in pH and decrease in log/O<sub>2</sub>. However, this precipitation path is inconsistent with mineral equilibria (see text for details).



Fig. 4-8

complexes predominate in very acid solutions (Wood et al., 1987; Belevantsev et al., 1998; Oelkers et al., 1998). Calculations using the program HCH (Shvarov, 1999; Shvarov and Bastrakov, 1999) indicate that for pH-log fO2 conditions in the pyrite field and temperatures between 250 and 500°C, the dominant antimony complex is Sb(OH)3<sup>0</sup>. Stibnite is usually associated with pyrite (Williams-Jones and Normand, 1997) in ore deposits, and is also the dominant Sb-sulfide at Hemlo. However, stibute solubility increases sharply with temperature, and hydrothermal fluids are unlikely to saturate at temperatures above ~300°C (Williams-Jones and Normand, 1997) and cannot do so at T > 350°C (the solubility exceeds  $\sim 10^{-2}$ m Sb at >350°C; Zotov et al., 2003). This raises important questions about the timing of deposition of antimonybearing minerals at Hemlo. For example, if stibnite precipitated before peak metamorphism, it would need to have done so at temperatures below 300°C and then be preserved through the remainder of the metamorphic cycle. The latter would only have been possible if fluid fluxes were minimal, which seems unlikely given that the mineralization is shear-zone hosted (and that rocks dewater during prograde metamorphism). Similarly, other antimony minerals, such as gudmundite and berthierite, also are unlikely to have formed early, as such phases are not stable in the pyrite stability field, have upper thermal stabilities below that of peak metamorphism, or require other ore elements (such as Fe, Pb, Bi, Ag, or Cu), which are either unavailable or insufficiently abundant to account for the present concentrations of Sb in the ore zones.

Arsenic transport in natural systems is dominated by hydroxide and sulfide complexes. In general, sulfide complexes predominate at temperatures <150°C and in

sulfide-rich (0.01 to 0.1 m H<sub>2</sub>S) solutions, whereas hydroxide species predominate at higher temperatures (Heinrich and Eadington, 1986; Wood et al., 1987, Ballantine and Moore, 1988; Spycher and Reed, 1989; Akinfiev et al., 1992; Pokrovski et al., 1996, 2002). Negatively charged arsenic hydroxide complexes form only at very alkaline conditions (Baes and Mesmer, 1976). At conditions inferred for the ore zones (i.e., pH and log/O<sub>2</sub> consistent with pyrite stability), the dominant complex would be H<sub>3</sub>AsO<sub>3</sub> {As[OH]<sub>3</sub>}. The most abundant arsenic-bearing minerals at Hemlo are realgar and orpiment, which are not stable at peak metamorphism, and therefore must have formed when the deposit cooled below the thermal stability of these minerals ( $307^{\circ}C$  and  $315^{\circ}C$  at 1 bar, respectively; Hall and Yund, 1964). Minor arsenopyrite occurs outside the ore zones at the edge of the sulfidation overprint on the wallrocks.

The maximum thermal stability of arsenopyrite is 702 °C (1 bar), which is above the temperature of peak metamorphism. However, at the high  $fS_2$  that would have prevailed in the ore zone, arsenopyrite could have melted at temperatures as low as 550 °C due to reactions such as arsenopyrite + pyrite  $\rightarrow$  pyrrhotite + melt (Frost et al., 2002). Moreover, it is debatable whether arsenopyrite was ever present in the Hemlo ore zones, as the inferred high  $fS_2$  conditions would have prevented its formation. The lack of even remnant arsenopyrite in these rocks suggests that this mineral only formed where  $fS_2$  was relatively low, i.e., at the edge and outside the ore zones (Fig. 4-9).

Other arsenic-bearing species that occur at Hemlo include minor tennantite  $\{(Cu,Hg)_{12}As_4S_{13}\}$ , and traces of aktashite  $\{Cu_6Hg_3As_4S_{12}\}$ , routhierite  $\{TlHgAsS_3\}$ ,

Figure 4-9.

 $Log fS_2$  – temperature relationships for selected Fe- and As-bearing minerals. Arsenopyrite is stable at intermediate  $log fS_2$  conditions and probably did not form at Hemlo, where ore zone conditions are defined by relatively high  $fS_2$  conditions (see text for details).



Fig. 4-9

and gersdorfite {NiAsS}. However, Cu, Tl and Ni are not sufficiently abundant to support reservoirs of As at elevated temperatures.

The above observations indicate that an alternative explanation is necessary for the precipitation and preservation of As and Sb at Hemlo. We propose that As and Sb were initially adsorbed onto pyrite growth surfaces during mineralization, and were subsequently released during metamorphic recrystallization. This process is relatively well documented in gold deposits where the substitution of As and Sb for S in pyrite is interpreted to create a distortion in the crystal lattice, which also permits the adsorption of elements such as Au and Pb (e.g., Fleet et al., 1989; Arehart et al., 1993); pyrite may contain up to 5 at. % As (Fleet et al., 1989), and as much as 1000 ppm Au has been observed in pyrite of the Fairchild deposit of South Africa (Fleet et al., 1993). Since pyrite is the most abundant sulfide mineral at Hemlo (ranging from 5 to 20 wt %, and averaging 8 wt % in the Golden Giant orebody; Brown et al., 1985), only minor incorporation of As and Sb would have been necessary to account for the concentrations of these metals currently present in the ore zones.

Deposition of the main stage native gold – molybdenite assemblage is readily explained by mineral stability and metal speciation relationships at 450 °C and 4 kb, which indicate that these minerals could have precipitated due to the decrease of pH and  $fO_2$ , which accompanied potassic alteration (reaction 5) and precipitation of pyrite (reaction 4), respectively (Fig. 4-8). However, these relationships also show that pH would have been the principal control on mineral deposition (see discussion on temperature and pressure constraints on mineralization). For example, assuming that the ore fluid had an initial pH of 6.5 and log $fO_2$  of -21.5 (conditions near the maximum solubility of both gold and molybdenite), the decrease of pH to  $\sim 4$  in the ore zone would have decreased Au and Mo solubility by 3 log units, whereas the corresponding decrease of log/O<sub>2</sub> by less then 1 log unit would only have decreased their solubility by 0.3 log units. At a pH of  $\sim 4.5$ , barite would have started dissolving (reaction 3), causing the precipitation of more pyrite and barian feldspar (hyalophane). Further decreases in pH and  $fO_2$  would have been prevented by the dissolution of barite, which increases both pH and  $fO_2$  and the equilibration of K-feldspar with muscovite, which fixes the pH at  $\sim 4.2$  (Fig. 4-8). (Note that a decrease in  $fO_2$  alone does not lead to the co-precipitation of molybdenite and gold).

Transport and deposition of gold as chloride complexes is also theoretically possible, but would require reduction of the mineralizing fluid. Typically, this involves the oxidation of phases/species containing Fe or S to form minerals such as hematite, magnetite, epidote or aqueous species such as  $SO_4^{2^-}$ . However, these minerals are absent or rare in the Hemlo ore zones and, as deposition had to occur in the pyrite stability field, H<sub>2</sub>S was the dominant species. This implies that the chloride complexes were probably not important in the transport of Au.

# The lack of copper

As discussed earlier, one of the models currently favored for the genesis of the Hemlo Au deposit is the porphyry model, which implies a predominantly magmatic mineralizing fluid. Porphyry deposits are characterized by a range of metal associations, from Au-Cu to Au-Cu-Mo to Cu-Mo; but gold-molybdenum mineralization without copper is uncommon. Lithogeochemical studies by Williams-

Jones et al. (1998) and Bodycomb et al. (2000) indicate that average Cu concentrations in the ore zones (~33 ppm) are essentially the same as those of the host rock lithologies (~31 ppm, Williams-Jones et al., 1998). Within the deposit, Cu is hosted mainly by tennantite-tetrahedrite and aktashite, whereas chalcopyrite predominates in the wallrocks. This zonation is consistent with higher  $fS_2$  in the ore zones.

The lack of copper enrichment in the ore zones indicates that either the fluid did not contain significant copper, or copper did not saturate due to its high solubility. Orthomagmatic hydrothermal systems with significant concentrations of Au, Mo, W, Sb, As and Te but low copper have been described in other ore deposits. An example is Fort Knox, Alaska (Hollister, 1991; Bakke, 1995; Newberry et al., 1995, McCoy et al., 1997), which is a large tonnage (>130 t Au) gold deposit that is inferred to be genetically associated with a copper-poor, relatively reduced (ilmenite-series) I-type granite. The deposit is enriched in Mo, Bi, W, As, Sb and Te, but is base metal-poor. Similar Cu-poor mineralizing fluids might therefore have been responsible for the mineralization at Hemlo. However, we prefer the explanation which has recently been proposed by Grondin and Williams-Jones (2004) for the absence of copper in typical mesothermal gold deposits, namely that at the  $fO_2$ -pH conditions of the ore fluids (similar to those proposed here) the solubility of copper is so high due to the stability of Cu(HS)<sub>2</sub><sup>-</sup> that rather than being deposited, Cu is actually leached from its surroundings.

## The genetic model

The two most widely accepted depositional models for the Hemlo ores, mesothermal and porphyry, are both consistent with ore formation at temperatures suggested by our thermodynamic modeling (400 to 500°C). However, the porphyry model proposes that the fluids are dominantly of magmatic origin, whereas mesothermal-orogenic deposits are commonly assumed to have formed by metamorphic fluids.

Higher temperatures for mineralization, such as those associated with peak metamorphism, are inconsistent with geochronological constraints that place the mineralization earlier (Davis and Lin, 2003). In addition, at these temperatures (>600°C), elements such as Sb and As are even more soluble than at greenschist conditions, and gold solubility in the pyrite stability field is too high for this element to precipitate (Fig. 4-10). At  $\Sigma$ aS lower than those plotted on Figure 4-10, the pyrite field shrinks progressively and disappears, which clearly did not occur at Hemlo. Therefore, a syn- or immediate pre-peak metamorphic timing for mineralization is considered unlikely.

Low temperature mineralization, such as that consistent with an epithermal origin (e.g., 250°C, 300 bars) could explain the abundance of As and Sb-bearing minerals, as minerals containing these elements can saturate at these conditions. On the other hand, it does not explain the occurrence of molybdenite, which is insoluble at the  $fO_2$ , pH and temperatures of gold transport and deposition in epithermal systems (i.e., <<1 ppb; Fig. 4-11). Molybdenum and gold could be transported together at high pH in the SO<sub>4</sub><sup>2-</sup> predominance field, and would precipitate in the pyrite stability

Figure 4-10.

 $Log O_2 - pH$  diagram showing solubility contours for Au and Mo and phase stability boundary for selected minerals at 600°C, 5 kb and  $log\Sigma aS = 0.3$ . Under these conditions, native gold can precipitate in the pyrrhotite stability field from either AuCl<sup>-</sup> and Au(HS)<sub>2</sub><sup>-</sup> complexes. By contrast, gold solubility in the pyrite stability field (shaded) is too high to account for deposition. Note that at lower total sulfur levels, the pyrite field shrinks and is absent at  $log\Sigma aS < -0.5$ . At higher  $\Sigma aS$  levels, the pyrite stability field expands, but corresponding increases in Au(HS)<sub>2</sub><sup>-</sup> prevent coprecipitation of pyrite and native gold.



Figure 4-11.

 $Log O_2 - pH$  diagram showing solubility contours for Au and Mo and phase relationships in the Fe-O-S system at 250°C and 300 bars (epithermal conditions). The solid circle shows possible ore fluid conditions (i.e., both Au and Mo have high solubilities). Note that in order to precipitate gold and molybdenite in the pyrite stability field (arrow), pH has to decrease from approximately ~9 to 4.5, which is unreasonable under most geological conditions (see text for details).



field after a decrease of 4 or 5 pH units. However, during this decrease in pH, Mo solubility would sharply decrease, whereas Au solubility would initially increase and then decrease in the pyrite stability field. Consequently, native gold and molybdenite would not form intergrowths, a texture that is commonly observed at Hemlo (Williams-Jones et al., 1998). Other features of the Hemlo deposit that are inconsistent with an epithermal model are the lack of vuggy silica or evidence of acid sulfate alteration (or their metamorphosed equivalents) and the paucity of veins (low sulfidation epithermal). Therefore, low temperature mineralization does not adequately explain the ore deposit systematics at Hemlo.

#### Magmatic versus metamorphic fluids

A wide range of fluid sources has been proposed for mesothermal deposits, including metamorphic devolatilization, volatile exsolution from mantle-derived felsic and mafic magmas, volatile exsolution from anatectic magmas, surface-derived and downward-circulating waters, and fluids liberated from subducting slabs or partially molten asthenosphere (e.g., Newton, 1989 and references therein). The most recent discussions have focused on fluids of metamorphic and magmatic origin. Despite evidence of an apparently significant magmatic component to the mineralizing fluids at Hemlo (extreme enrichment of Mo and K ), a contribution by metamorphic fluids cannot be ruled out as the deposit is shear zone-hosted, and is interpreted to have been emplaced during prograde metamorphism (Heiligmann et al., Chapter 3). Indeed, the syn-metamorphic timing of Hemlo mineralization, albeit prior to the metamorphic

peak, make it very likely that some metamorphically derived fluids rose through the shear zones that host the deposit.

An igneous source for the Hemlo ore fluids was invoked by Johnson (1996), who proposed that the quartz-feldspar porphyry (Moose Lake), located between the Main and Lower ore zones, is the deformed equivalent of a porphyry stock. However, the presence of lapilli fragments and relict primary layering indicate that much of this unit is extrusive (Muir, 1997; Williams-Jones et al., 1998), and is therefore unlikely to have been the source of mineralizing fluids. Another potential source for magmatic fluid is the Heron Bay pluton. Although emplaced  $\sim 7$  km from the deposit, this magma could have evolved a volatile fluid phase that migrated laterally into the deposit area (Beakhouse, 1998). Some feldspar porphyry dikes in the deposit area are genetically related to the Heron Bay pluton, which locally has a finer-grained plagioclase-phyric phase, and has been interpreted to have been quenched due to a decrease in hydrostatic pressure and release of a volatile phase (Beakhouse, 1998). This fluid could have been focussed into the deposit area by extensional structures, but there is no evidence for this scenario. It is also not evident that a fluid exsolved from the Heron Bay pluton could travel ~7 km laterally to the Hemlo area. In general, buoyancy flow requires near hydrostatic pressure gradients, and is thought to be efficient only in the upper crust (e.g., Connolly, 1997). At mid- and lower crustal levels, fluid flow is mainly pressure driven (Connolly, 1997), which implies that upper crustal mineralization is unlikely to have originated from Heron Bay source fluids. At mid-crustal levels, a fluid originating from the pluton would have been separated from the deposit by the Hemlo fault zone, which is not mineralized. Consequently, such a

fluid would have had to cross the fault zone without leaking towards the surface, which seems unlikely. Finally, there is no sign of potassic alteration or Au-Mo mineralization in the vicinity of the pluton. Therefore, without further evidence, the Heron Bay pluton is considered to be an unlikely source for mineralizing fluids at Hemlo.

An unexposed pluton at depth is another possible fluid source for mineralization, and has been proposed by Kuhns et al. (1994), Muir (1997), Williams-Jones et al. (1998), and Beakhouse (1998). For example, Beakhouse (1998) speculated that minor intrusions in the Hemlo area, such as the Botham Lake stock may be part of a deeper, relatively large intrusion. Magmatic fluids would have migrated upwards along the Lake Superior shear zone and Moose Lake fault zone and eventually precipitated ore metals. However, a deep structure that channeled magmatic fluids could also provide a conduit for more typical mesothermal fluids.

## Porphyry versus mesothermal

As noted above, the Hemlo Au-Mo deposit has certain consistencies with both porphyry and mesothermal-orogenic genetic models, but in many respects is inconsistent with them. In general, porphyry mineralization is interpreted to result from a predominantly magmatic fluid that forms stockworks and veins at relatively shallow crustal levels. Although, such a fluid at Hemlo would partly explain the ore zone mineral assemblages (K-feldspar and molybdenite), the lack of a genetically associated intrusion, the disseminated nature of the mineralization, the location of the deposit in shear zones, the lack of Cu enrichment, and the depth of emplacement are

features that are incompatible with porphyry models. Thus, if Hemlo was the product of magmatic fluids, the related intrusion would have to have been very deep-seated. This intrusion would clearly not have been porphyritic.

A mesothermal-orogenic model for Hemlo is consistent with the tectonic setting, timing of mineralization and some of the element enrichment trends, but Hemlo differs from most mesothermal-orogenic deposits in the nature of the alteration (potassic), and some aspects of mineralization (e.g., presence of molybdenite). In contrast to Hemlo, typical mesothermal-orogenic deposits are associated with carbonate alteration and albitization in greenschist facies rocks, or with calc-silicate alteration in rocks metamorphosed to amphibolite and granulite facies (Groves, 1993). These alteration assemblages are consistent with a low-NaCl, CO<sub>2</sub>-rich metamorphic fluid that equilibrated with a typical greenstone assemblage. A predominantly metamorphic fluid, produced by the dewatering of large sections of the crust has commonly been proposed for mesothermal-orogenic deposits (e.g., Kerrich, 1993; McCuaig and Kerrich, 1998; Groves et al., 1998) and is, in part, based on the observation that these deposits have similar element enrichment profiles (e.g., Au, Sb, As, Hg, W; Kerrich, 1993; McCuaig and Kerrich, 1998), which contrast with the wide diversity of spatially associated igneous rocks. Although, these elements are all enriched at Hemlo, the extreme enrichment in Mo and K is atypical of mesothermal mineralization and more consistent with a magmatic fluid source. However, isotopic evidence indicates that a significant magmatic component to some mesothermalorogenic deposits cannot be ruled out (e.g., Heinrich et al., 2000) and several fault and shear zone-hosted gold deposits have features that are incompatible with a
predominantly metamorphic fluid origin. Indeed, Groves et al. (2003) suggested that 'intrusion-related' and several 'anomalous' structurally-hosted deposits (e.g., Hemlo and Hollinger-McIntyre), have important similarities to mesothermal-orogenic mineralization (such as tectonic regime, narrow structural setting, trace element distribution), but are unlikely to have formed from a predominantly metamorphic source fluid. In the case of Hemlo, these authors proposed a multistage epithermal model (Groves et al., 2003), which as discussed earlier, is inconsistent with geochronological, structural and geochemical data.

A magmatic component to a mesothermal-orogenic source fluid is geologically reasonable as anatexis and intrusion-related dewatering occur in the crust, and is consistent with the isotopic data (Heinrich et al., 2000). In the orogenic model, these fluids are interpreted to mix with vastly greater quantities of metamorphic fluids. However, if a deposit forms relatively close to an unexposed intrusion, as has been postulated for Hemlo, the magmatic characteristics of the mineralizing fluid should be clearly recognizable. This suggests that Hemlo might represent an example of a deposit intermediate to the endmembers 'metamorphically-dominated orogenic' and 'intrusion-related' or 'deep magmatic-hydrothermal'. The magmatic component would account for the extreme enrichment in elements such as Mo and K, whereas the confinement of the deposit to a narrow structural corridor, and the disseminated nature of the mineralization are consistent with a mesothermal-orogenic setting. This conclusion is also consistent with the range of alteration assemblages associated with mesothermal-orogenic deposits, which include quartz-carbonate-albite, calc-silicate and K-feldspar-biotite; in some cases the K-feldspar-biotite and one of the other

assemblages may accompany mineralization in a single deposit (e.g., Pirajno, 1992). The first two assemblages are consistent with fluids resulting from metamorphic devolatilization of the crust and alteration at low and high temperature, respectively. By contrast, K-feldspar-biotite assemblages may be related to magmatic fluids. If this interpretation is correct, then fluids forming other mesothermal-orogenic deposits with appreciable K-feldspar and/or biotite alteration also had a significant magmatic component.

#### Conclusions

Amphibolite-facies metamorphism overprinted potassic alteration and mineralization at Hemlo, and direct evidence of the origin of mineralizing fluids was destroyed by recrystallization. Thermodynamic modeling indicates that ore zone conditions were buffered by the dissolution of barite, deposition of pyrite, and equilibrium between muscovite and K-feldspar. Mineralization occurred at greenschist facies conditions (400 to 500°C) through a decrease in pH and an increase in  $fO_2$  in the pyrite stability field. These changes resulted mainly from potassic alteration, precipitation of pyrite and dissolution of barite. Native gold and molybdenite precipitated directly from the mineralizing fluid, and ore-related elements such as As and Sb (and possibly Au) were adsorbed onto pyrite, from which they were released during subsequent peak metamorphic recrystallization.

An epithermal origin for the mineralization can be ruled out because of the lack of high sulfidation minerals, the lack of a vein system (low sulfidation subclass) and the very low solubility of molybdenite in either high or low sulfidation systems. Although As and Sb have relatively low solubility at epithermal conditions and often form realgar, arsenopyrite and stibnite, respectively, the preservation of these minerals during prograde metamorphism is compromised by the strong increase in their solubility with increasing temperature and their low thermal stability. Finally, an epithermal model is inconsistent with structural and geochronological constraints that have been established for the mineralization.

The Hemlo gold deposit has geological and geochemical characteristics that are consistent with both magmatic-hydrothermal ('porphyry') and mesothermalorogenic depositional models, but are typical of neither. The strong enrichment in Mo and the pervasive potassic alteration point to magmatic fluids, whereas the structural setting, element enrichment trends, and lack of Cu are more consistent with a mesothermal-orogenic origin. This implies that Hemlo is either a deep-seated, structurally hosted magmatic-hydrothermal deposit, or a mesothermal-orogenic deposit with a significant magmatic component. This study suggests that there is that a continuum between magmatic hydrothermal deposits and predominantly metamorphogenic orogenic deposits.

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Previous chapters of this thesis describe the metamorphic setting and mineralization of the Hemlo gold deposit. During peak and retrograde metamorphism, some mineralization was remobilized, as is evident from the common association of gold with low temperature minerals such as stibnite and realgar (these minerals have upper thermal stabilities below that of peak metamorphism). Chapter V investigates the extent and distribution of low temperature sulfides in the ore zones and evaluates how these elements (e.g., Au, Sb, As, Hg and Pb) were remobilized.

# **Chapter V**

# Metamorphic remobilization of ores in the Hemlo gold deposit, Ontario

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### Abstract

The controversy over the origin of the Hemlo gold deposit of north-central Ontario is due, in part, to metamorphic remobilization. The mineralization occurs mainly as native gold and molybdenite in deformed and recrystallized potassically altered rocks, consistent with emplacement prior to peak metamorphism. However, significant gold (as the native metal) is also associated with low temperature sulfide minerals (e.g., stibnite, realgar), which were not stable at peak metamorphic conditions. In addition, minor gold related to calc-silicate (and sericitic) alteration, occurs in small veins and fractures that cross-cut the ore zones and contain assemblages indicative of hydrothermal formation at ~400°C.

Gold associated with low temperature sulfides, dominantly Sb- and As-bearing minerals, such as stibnite, native antimony, realgar, native arsenic and tennantitetetrahedrite, occurs throughout the deposit. These minerals are generally present as solid inclusions on secondary planes and as isolated crystals or aggregates of crystals on silicate grain boundaries, and are considered to represent remobilization from main stage mineralization during peak metamorphism.

The low thermal stability of the secondary As- and Sb-bearing minerals, the absence of aqueous liquid-bearing inclusions in solid inclusion planes (except near intersections with fluid inclusion planes), the extremely high solubility of stibnite above  $300^{\circ}$ C, and the evidence of contrasting  $fS_2$  conditions (realgar and native arsenic or stibnite and native antimony in the same rocks), suggest that a hydrothermal origin is unlikely. These characteristics are, however, consistent with protracted crystallization from a sulfide melt that formed at or near peak metamorphic conditions.

We propose that this sulfide melt formed by exsolution of elements such as As and Sb from pyrite during metamorphic recrystallization, melting of primary minerals (such as Hg-bearing native gold), and the interaction of melt with aqueous metamorphic fluids carrying sulfur. Ore-related assemblages are similar to those predicted by experimental data for the As-Sb-S and related systems, and are interpreted to have formed by fractional crystallization of the sulfide melt.

## Introduction

Metamorphosed ore deposits commonly display textural, mineralogical and chemical evidence of remobilization (Marshall and Spry, 2000), and failure to recognize or appreciate its extent may make genetic interpretations difficult or contentious (e.g., Sangster, 1971; Marshall and Gilligan, 1993; Plimer, 1987; Marshall and Spry, 2000). An example is the worldclass Hemlo gold deposit of north-central Ontario (95 million tons of ~8 g/t Au; Schnieders et al., 2000), which has been variously interpreted as a post-peak metamorphic skarn (Pan and Fleet, 1992, 1995), a syn-peak metamorphic mesothermal deposit (Burk et al., 1986), and a variety of prepeak metamorphic deposit types including epithermal (e.g., Goldie, 1985), porphyry (Kuhns et al., 1994; Johnston, 1996) and mesothermal-orogenic (e.g., Muir, 2002). However, there is a growing consensus that the bulk of the gold was introduced prior to peak metamorphism (e.g., Kuhns et al., 1994; Muir, 1997, 2002; Powell and Pattison, 1997; Williams-Jones et al., 1998; Lin, 2001; Davis and Lin, 2003, Tomkins et al., 2004; Heiligmann et al., Chapter 3), and that some gold was subsequently remobilized.

Primary gold mineralization occurs mainly as Hg- and Ag-bearing native gold, associated spatially with molybdenite in potassically altered rocks containing Kfeldspar and muscovite, which were recrystallized during peak metamorphism (630°C, 5 to 7 kb). Appreciable gold is also associated with late low temperature sulfide minerals (such as stibnite and realgar), and to a lesser extent, with calc-silicate alteration; however, the importance of these secondary associations is contentious.

Gold associated with calc-silicate alteration occurs in relatively undeformed veins and fractures, and was interpreted by Pan and Fleet (1995) to represent a postpeak metamorphic mineralization event that accounts for most of the ore at Hemlo. This interpretation is in conflict with most other studies of Hemlo, which have concluded that gold associated with calc-silicate alteration accounts for a very minor proportion of the ore, and that it represents late-stage hydrothermal remobilization rather than primary mineralization (e.g., Kuhns et al., 1994; Muir, 1997, 2002; Powell and Pattison, 1997; Williams-Jones et al., 1998; Heiligmann et al., Chapter 4). In fact, most of the remobilized gold is disseminated with low temperature sulfide minerals in boudins, veins and fold hinges that are not spatially associated with calc-silicate alteration. These sulfides (e.g., realgar and stibnite) have upper thermal stabilities well below the temperature of peak metamorphism, and therefore must have formed during retrograde cooling, but there is little agreement on the origin of this second type of remobilization. Williams-Jones et al. (1998) noted that ore-related elements, such as antimony and arsenic, are highly soluble at peak metamorphic temperatures (~630°C), and suggested that they could have been mobilized by post-peak metamorphic fluid infiltration, and re-deposited in lower temperature quartz and later calc-silicate veins. By contrast, Powell and Pattison (1997) proposed that the low temperature minerals were produced by exsolution from a hypothetical As-Hg-Cu-Zn-Fe-bearing antimonian sulfosalt, which was stable only during peak metamorphism. Finally, Heiligmann et al. (2003) and Tomkins et al. (2003; 2004) proposed that the low temperature sulfide minerals crystallized from a sulfide melt that formed during peak metamorphism. According to this hypothesis the melt migrated into dilational

domains, such as boudin necks and extensional fractures, and progressively crystallized a suite of minerals including stibnite, realgar, sulfosalts, intermetallic compounds and tellurides, as the rocks cooled to a temperature of ~300°C.

This paper investigates the evolution of the Hemlo gold deposit during retrograde metamorphic cooling, and assesses the role of fluid infiltration, exsolution and melting in the remobilization of gold and related sulfides. In addition, the significance of late-stage hydrothermal activity (associated with calc-silicate and sericitic alteration), in controlling the distribution of gold is also evaluated.

### **Geological setting**

The Hemlo gold deposit is located in the Archean Hemlo-Heron Bay greenstone belt of north-central Ontario. Mineralization occurs predominantly in two sub-parallel ore zones, which coincide with the Lake Superior shear zone and the Moose Lake fault zone (Fig. 5-1; Muir, 2002). Both ore zones grade outwards into metasediments, including metamorphosed sandstones, wackes, pelites and marls (Fig. 5-2). Metasediments in the hangingwall (north) and footwall (south) are geochemically indistinguishable from each other (Williams-Jones et al., 1998), and are interpreted to represent the limbs of a proto-sheath fold (Lin, 2001). The Lower ore zone occurs at the contact of footwall metasediments with quartz-feldspar porphyry unit with hangingwall metasediments, and locally a mafic fragmental unit (which only occurs in the hangingwall). Mineralization is hosted mainly by metasediments (including barite, sandstones, wackes, pelites and marls) and to a lesser extent by

Figure 5-1.

Geological map of the Hemlo area (modified from Muir, 1997), showing the location of mines and the distribution of mineralization (black). Note that the Lake Superior shear zone (LSSZ) and Moose Lake fault zone (MLFZ) coincide with the Main and Lower ore zones, respectively.





Figure 5-2.

Simplified cross section through the Golden Giant mine, located approximately in the center of the deposit. Mineralization occurs at the contact between footwall metasediments (including wackes, marls and pelites) and quartz-feldspar porphyry rocks (Lower ore zone), and between the quartz-feldspar porphyry and hangingwall metasediments (including wackes, marls and pelites) and the mafic fragmental unit (Main ore zone) (modified from Sutcliffe, 1998).



# LEGEND



Ore zones (Main and Lower)





quartz-feldspar porphyry and altered mafic fragmental rocks. The origin of some of these units is contentious. Thus, the baritic unit is considered to be either a chemical sediment (Cameron and Hattori, 1985; Thode et al., 1991; Williams-Jones et al., 1998) or the product of hydrothermal alteration associated with mineralization (Muir, 2002), and the porphyritic rocks are interpreted to be either felsic volcanic (Muir, 1997, 2002; Williams-Jones et al., 1998) or intrusive rocks (Johnston, 1996). The precursor lithology of the mafic fragmental unit, which is characterized by felsic fragments in a predominantly mafic matrix, has been interpreted as either a mafic conglomerate (Burk, 1987), mafic volcaniclastic unit (Kuhns et al., 1994), hydrothermal breccia (Johnston, 1996), biotitized felsic unit (Lin, 2001), or an analog to a Temiskaming-type conglomerate (Heiligmann et al., Chapter 2).

#### **Metamorphism**

Peak metamorphic conditions were in the amphibolite-facies, as shown by the widespread occurrence of the assemblage biotite-garnet-staurolite-kyanite/sillimanite in metapelites, and amphibole-plagioclase in metabasites (Burk et al., 1986; Kuhns et al., 1994; Pan and Fleet, 1992, 1995; Powell et al., 1999; Heiligmann et al., Chapter 3). However, there is disagreement on the number of prograde metamorphic episodes, the importance of retrograde metamorphism, or the temperature and pressure of peak metamorphism. The most extensive study to date (Heiligmann et al., Chapter 3) concluded that peak metamorphism occurred at a temperature of  $\sim$ 630°C and a pressure of between 5 and 7 kb. Geochronological data indicate that prograde heating occurred during a relatively restricted period of  $\sim$ 10 to 15 Ma, followed by slow retrograde cooling (3 to 7 °C/Ma) that spanned an interval of  $\sim$ 80 Ma (Williams-Jones

et al., 1998; Heiligmann et al., Chapter 3). Peak metamorphic assemblages were locally overprinted by lower grade minerals such as chlorite (oblique overgrowth on biotite), and tremolite (rims on hornblende in the mafic fragmental unit). The presence of these minerals indicates that late-stage fluids locally infiltrated the deposit area during retrograde metamorphism.

### Alteration

Ore zone rocks can be subdivided into microcline-, muscovite- and biotite-rich facies, which are interpreted to represent the products of hydrothermal alteration recrystallized during regional metamorphism; microcline exhibits triple junctions, whereas micas define the predominant foliation. A central K-feldspar-rich facies grades outwards into mainly muscovitic rocks, considered to reflect progressively decreasing  $aK^+$  during alteration (Heiligmann et al., Chapter 2). Biotitic alteration was strongest in mafic fragmental rocks, in which biotite and lesser microcline and muscovite are inferred to have replaced amphibole (Heiligmann et al., Chapter 2).

Heiligmann et al. (Chapter 2) showed that ore zone assemblages were modified by sulfidation reactions that occurred during mineralization, and that this continued through the metamorphic cycle (Heiligmann et al., Chapter 2). High  $fS_2$  conditions in the ore zones are interpreted to have resulted from the progressive dissolution of barite, which inhibited the formation of Fe-oxide and most Fe-silicate minerals. In these zones, ilmenite, magnetite and metamorphic index minerals, such as garnet and staurolite, are absent, whereas they occur in wallrocks, generally within meters of gold mineralization. In addition, biotite, which is annitic in the country rocks, is

phlogopitic in altered and mineralized rocks. This resulted from preferential partitioning of iron into pyrite, which is the main Fe-bearing mineral in the deposit; owing to the high- $fS_2$  conditions during peak metamorphism, pyrite was not transformed into pyrrhotite (Heiligmann et al., Chapter 2).

Ore-related alteration was overprinted locally by coincident calc-silicate and sericitic assemblages. There is disagreement over the importance and extent of this late-stage alteration, with some studies suggesting that calc-silicate assemblages host the bulk of the mineralization (Pan and Fleet, 1995), and others relegating this style of alteration to a late-stage bleaching event (Kuhns, 1988). The post-peak metamorphic calc-silicate event is characterized by thin veins, fractures and alteration zones that are not penetratively deformed, and occur in both ore zones and surrounding rocks. These zones contain amphiboles, calcite, epidote, garnet, zoisite, vesuvianite, titanite, diopside, pumpellyite and prehnite. Assemblages involving these minerals are representative of low to intermediate-grade metamorphism, and Pan and Fleet (1993) suggested that they formed at temperatures between 300 and 400°C and a pressure <2kb. These authors also suggested that Hemlo is a skarn-type deposit because of local intergrowth of calc-silicate minerals with minor amounts of native Au (Pan and Fleet, 1995). However, most gold at Hemlo is not spatially associated with calc-silicate alteration, and similar alteration outside the ore zones is barren. Thus calc-silicate alteration did not accompany major gold mineralization, but did locally remobilize gold introduced earlier (Williams-Jones et al., 1998).

### *Mineralization*

Gold mineralization at Hemlo is interpreted to have been deposited under greenschist facies conditions during prograde regional metamorphism (Heiligmann et al., Chapter 4). This interpretation is based on thermodynamic modeling of the mineralization, geochemical and geochronological constraints (e.g., the kinetics of the barite-pyrite isotopic exchange; U-Pb isotope geochronology), as well as textural and mineralogical observations, such as the relationships between sulfides and metamorphic index minerals. The spatial distribution of Au, Mo, As and Sb (their peak concentrations generally coincide in the ore zones) suggests that these elements were all concentrated during a single primary mineralization event (Williams-Jones et al., 1998; Heiligmann et al., Chapter 4).

The gold mineralization is characterized mainly by Hg- and Ag-bearing native gold in baritic and potassically-altered metasediments, and to a lesser extent in quartz-feldspar porphyry and mafic fragmental rocks (Williams-Jones et al., 1998). Native gold occurs typically as small (1 to 40  $\mu$ m) subequant grains, interstitial to or within microcline, quartz, barite and muscovite, and at contacts between these minerals and molybdenite, pyrite, stibnite and less commonly realgar (Williams-Jones et al., 1998). Gold also occurs in later deformed, syn-metamorphic quartz veins and pods, where it is commonly associated with minerals such as stibnite and realgar (Williams-Jones et al., 1998), which have upper thermal stabilities of 556 and 315°C (at 1 bar), respectively. This latter association indicates that gold and ore-related minerals were remobilized during metamorphism.

The origin of the gold mineralization at Hemlo is controversial, as is evident from the large number of proposed genetic models. We favor a mesothermal-orogenic model that includes an important role for magmatic fluid; this model accounts for the disseminated nature of the primary ore, the association of gold mineralization with shear zones, and the strong associated enrichments in K and Mo (Heiligmann et al., Chapter 4). Primary Au-Mo mineralization occurs as finely disseminated grains, interpreted to result from formation in a predominantly ductile setting. Thermodynamic modeling indicates that the gold and molybdenite were deposited at temperatures between 400 and 500 °C (and 3 to 5 kb) in response to a decrease in pH caused by potassic alteration and precipitation of pyrite (Heiligmann et al., Chapter 4). Metasedimentary barite dissolved, which increased sulfur fugacity in the vicinity of the ore zones. At these conditions, Au and Mo co-precipitated from the ore fluid. By contrast, stibnite is highly soluble at these temperatures, and would require unreasonably high concentrations to precipitate from a hydrothermal fluid (e.g., Williams-Jones and Normand, 1997; Zotov et al., 2003). Instead, Sb, As and some Au are interpreted to have been adsorbed during pyrite deposition, a process that is welldocumented in other mineral deposits (e.g., Cook and Chryssoulis, 1990; Arehart et al., 1993; Fleet et al., 1993; Tanocai et al., 1997; Ashley et al., 2000; Hofstra and Cline, 2000; Pals et al., 2003, Chouinard et al., 2005). Most common Sb- and Asbearing minerals either have unreasonably high solubility, decompose at temperatures below 400 °C (e.g., realgar and orpiment), or could not form at the relatively high  $fS_2$ conditions of mineralization (e.g., arsenopyrite; see below).

### **Solid inclusions**

Low temperature sulfide minerals occur in most ore zone rocks, and are locally intergrown with native gold, aurostibite and rare gold tellurides. These minerals have two modes of occurrence: as solid inclusions in silicate minerals such as quartz, and as clusters and aggregates on grain boundaries (Fig. 5-3). Solid inclusion trails in ore zone rocks are relatively abundant, and inclusions range from 1 to 15 µm in diameter; most are monophase, with realgar being the most common mineral. However, some are polyphase containing two or three minerals, and locally up to five minerals. Along individual planes, phase ratios in polyphase inclusions are usually constant. Solid inclusions on these secondary planes do not contain liquid or vapor, except where the planes have been cut by planes of fluid inclusions. At these intersections, the inclusions comprise solid, liquid and vapor, interpreted to have formed as a result of local incorporation of solid (sulfides) during fluid entrapment (Fig. 5-4). Elsewhere the fluid inclusions comprise only liquid, liquid and vapor or locally, liquid, vapor and halite.

Solid inclusion trails commonly radiate outwards from sulfide 'clusters' (Fig. 5-4), suggesting prolonged remobilization of ore-related metals. Low temperature sulfides at grain boundaries occur as 10  $\mu$ m to >1 cm diameter monophase or polyphase clusters, and are generally dominated by Sb- and As-bearing minerals, such as stibnite, native antimony, realgar, native arsenic and tennantite-tetrahedrite, many of which decompose at temperatures well below that of peak metamorphism (e.g., realgar, orpiment, stibnite; Table 5-1). This, and the evidence presented elsewhere (Heiligmann et al., Chapter 4) that Au, Mo, As and Sb were all concentrated in a

### Figure 5-3.

Photomicrographs of ore minerals at Hemlo in the system As-Sb-S.

- (A) Intergrowth of stibnite, native antimony and pääkkönenite.
- (B) Intergrowth of stibnite and native gold. This assemblage is relatively common at Hemlo and occurs commonly in quartz veins.
- (C) Native arsenic in a quartz vein (note the characteristic 'ice fern' texture).
- (D) Polyphase melt inclusions are relatively common in quartz veins and, generally, are not associated with any fluid.
- (E) Monophase realgar inclusions in quartz. Realgar has an upper thermal stability of ~307°C, indicating formation late during the retrograde stage of metamorphism.
- (F) Polyphase realgar-orpiment inclusion in quartz. The upper thermal stability of orpiment is ~315°C.
- (G) Realgar-stibnite and realgar-native Au in quartz. The association of gold with realgar suggests that gold was remobilized at relatively low temperatures.
- (H) Polyphase inclusion planes in quartz. Note that polyphase inclusions on secondary fractures contain similar phase ratios.

(see discussion for interpretations of these textures)



Fig. 5-3



Fig. 5-3. (continued)

Figure 5-4.

Photomicrographs of ore and late-stage alteration minerals at Hemlo.

- (A) Fluid inclusions with trapped sulfide minerals. This type of inclusion is rare at Hemlo and forms only at the intersection of solid and fluid inclusion trails.
- (B) Distribution of sulfide minerals in quartz vein. Solid inclusions trails locally radiate outwards from a central sulfide 'cluster'.
- (C) Realgar, titanite and sericite in sericitic (calc-silicate?) alteration zone.
- (D) Same photo as C, but with crossed nichols. Sericitic alteration zones generally appear to displace low temperature sulfides, such as realgar.

(see text for interpretations of these textures)



Fig. 5-4
. <u></u>	Mineral	T (°C) (±)	Reference
As-S	realgar + arsenic	281 (5)	Hall and Yund (1964)
	realgar	307 (5)	Hall and Yund (1964)
	orpiment	315 (5)	Hall and Yund (1964)
	arsenic + melt	797 (5)	Barton (1969)
As-Sb	arsenic-antimony solid solution	612	Skinner (1965)
Fe-As-S	pyrite + arsenic = arsenopyrite + AsS-rich melt	363 (50)	Barton (1969)
	<pre>pyrite + arsenopyrite = pyrrhotite + AsS-rich melt</pre>	492 (12)	Clark (1960)
	arsenopyrite + arsenic = loellingite + AsS-rich melt	688 (3)	Clark (1960)
	arsenopyrite = loellingite + pyrrhotite + AsS-rich melt	702 (3)	Clark (1960)
	loellingite + AsS-rich melt = pyrrhotite + arsenic melt	825 (15)	Clark (1960)
As-Sb-S	pääkkönenite	535 (5)	Craig et al., (1974)
	wakabayashilite		
	getchellite	340-355	Weissberg (1965)
	duranusite		
Au-Sb	aurostibnite + gold	360	Hansen and Anderko (1958)
	aurostibite + native Sb	460	Hansen and Anderko (1958)
Au-Te	calaverite	464	Okamoto and Massalski (1984)
Ha-S	cinnabar + sulfur melt	315 (3)	Potter and Parner (1978)
ng-o	cinnabar	345 (2)	Potter and Barnes (1978)
Fe-S-Sb	gudmundite	280 (10)	Clark (1966b)
	stibnite+sultur melt + pyrite = melt	494 (5)	Barton (1971)
	stibnite + antimony + berthierite = melt	516 (5)	Barton (1971)
	berthierite + antimony = pyrrhotite + melt	530	Barton (1971)
	pyrite + berthierite = pyrrhotite + stibnite	532 (5)	Barton (1971)
	pyrite + stibnite = pyrrhotite + melt	545 (5)	Barton (1971)
	pyrite + stibnite = berthierite + melt	548 (5)	Barton (1971)
	berthierite = pyrrhotite + melt	563 (5)	Barton (1971)
Pb-S-Sb	zinkenite + boulangerite = robinsonite	318	Craig et al. (1973)
	zinkenite + stibnite = melt	523 (3)	
	zinkenite = robinsonite + melt	545 (5)	
	robinsonite + boulangerite = $Pb_3Sb_4S_9$	576	Chang and Bever (1973)
	robinsonite = Pb <sub>3</sub> Sb <sub>4</sub> S <sub>9</sub> + melt	582 (2)	Craig et al. (1973)
	boulangerite = $Pb_3Sb_4S_9$ + melt	638 (2)	Craig et al. (1973)
Cu-S-Sb	tetrahedrite = digenite + famatinite+ high skinnerite	543 (2)	Skinner et al., (1972)
As-Cu-S-Sb	tennantite + chałcostibnite -> high skinnerite + Cu₄(As,SI	392 (35)	Luce et al. (1977)
	Ag-tetrahedrite (endmember)	485	
	Cu-tetrahedrite (endmember)	610	
As-Cu-Fe-S	arsenopyrite + chalcopyrite -> tennantite + pyrite	400 (50)	Sugaki (1957)
As-Cu-S	tennantite -> melt	665	Maske and Skinner (1971)
Zn-S	sphalerite -> wurtzite (ZnS both) + melt	1670	Sharp (1969)
Ni-As-S	gersdorffite -> 'decomposition products'	>700	Yund (1962)
Pb-S	galena -> mełt	1027 (5)	Van Hook (1960)
Cu-Pb-S-Sb	bournonite (incongruent melting)	522 (3)	Frumar et al. (1973)

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Table 1. Upper thermal stability of selected minerals and mineral assemblages found in the Hemlo gold deposit.

single pre-peak metamorphic event, suggest that the solid inclusions were the products of extensive peak and post-peak metamorphic remobilization of the primary ores.

#### Compositions and distribution of low temperature sulfides

Compositions of low temperature sulfides were evaluated by microprobe analyses (EDS, WDS), and indicate that these minerals contain mainly the elements Sb, As, Cu, Pb and Hg. Most of the minerals are As- and Sb-bearing, which is consistent with bulk rock data from the ore zones showing that Sb and As are the most concentrated of the five metals listed above (Sb 311 ppm, As 211 ppm, Cu 42 ppm, Pb 30 ppm, Hg 28 ppm; Williams-Jones et al., 1998). In the As-Sb-S system the following minerals were identified: stibnite, realgar, pääkkönenite (Sb<sub>2</sub>AsS<sub>2</sub>), native antimony and arsenic, orpiment, and rare stibarsen (SbAs), wakabayashilite (As<sub>8.25</sub>Sb<sub>2.75</sub>S<sub>18</sub>), getchellite (AsSbS<sub>3</sub>), and duranusite (As<sub>4</sub>S), and occur either individually, or intergrown as complex assemblages (Fig. 5-5). Other relatively common minerals include tennantite-tetrahedrite, cinnabar and a variety of other sulfosalts (e.g., zinkenite, boulangerite, bournonite, twinnite, and berthierite).

Despite the widespread occurrence of stibnite and realgar at Hemlo, there are subtle differences in their distribution. Individual stibnite grains (i.e., grains that are not intergrown with other As-Sb-S minerals), occur overwhelmingly at grain boundaries, where they are locally associated with native gold. By contrast, stibnite hosted by solid inclusions on secondary fracture planes is generally accompanied by minerals such as realgar and orpiment. Pääkkönenite, native antimony and arsenic also occur predominantly on grain boundaries, where they form assemblages such as

Figure 5-5.

Minerals in the As-Sb-S system present at Hemlo. Although stibnite and realgar are the most abundant As- and Sb-bearing sulfides at Hemlo, a wide range of other minerals occur in the ore zones.



Fig. 5-5

stibnite-pääkkönenite-native antimony (photo), stibnite-pääkkönenite-stibarsen, and stibnite-pääkkönenite-native antimony±native arsenic. Native arsenic occurs locally as isolated crystals on grain boundaries, where it is commonly rimmed by As-oxide (Fig. 5-3), but was not observed in solid inclusions.

The only common minerals on secondary planes are realgar (Fig. 5-3) and to a lesser extent orpiment, which comprise the majority of monophase inclusions. In polyphase inclusions, the assemblages include stibnite-realgar, stibnite-orpiment, stibnite-getchellite-wakabayashilite, and stibnite-wakabayashilite-orpiment. A single isolated grain of duranusite in a solid inclusion in quartz was also observed. In addition to minerals in the As-Sb-S system, polyphase inclusions also contain assemblages such as stibnite-realgar-zinkenite, stibnite-coloradoite (HgTe)-realgar, and realgar-cinnabar.

# Discussion

#### **Remobilization of low temperature sulfides**

The origin and remobilization of the low temperature sulfides at Hemlo has been variously attributed to fluid infiltration (e.g., Williams-Jones et al., 1998), solid state exsolution (Powell and Pattison, 1997), and formation of a sulfide melt (Tomkins et al., 2003; Heiligmann et al., 2003). However, the low thermal stability of many of the sulfide minerals at Hemlo, the absence of aqueous liquid-bearing inclusions in solid inclusion planes (except near intersections with fluid inclusion planes), the extremely high solubility of stibnite above a temperature of 300°C, and the evidence of contrasting  $fS_2$  conditions, suggest that a hydrothermal origin for these minerals is unlikely.

Powell and Pattison (1997) suggested that assemblages of low temperature minerals (e.g., stibnite, realgar, and aktashite) formed as a result of their exsolution from a complex As-, Hg-, Pb- and Cu-bearing antimonian sulfosalt, which survived peak metamorphism but broke down completely during retrograde cooling. This unidentified sulfosalt was interpreted to be extremely ductile, and to have migrated into low-pressure regions during deformation. However, we interpret exsolution to be a rare and localized phenomenon (e.g., extremely rare intergrowths of native gold and cinnabar, inclusions of cinnabar in Hg-rich sphalerite, or stibnite with inclusions of native antimony), that does not account for the origin or distribution of low temperature sulfides on secondary inclusion trails, or in low pressure areas such as veins and boudins. Furthermore, the inferred highly ductile nature of this proposed sulfosalt (Powell and Pattison, 1997) does not adequately explain the distribution of these minerals, as even the most ductile mineral would not have flowed to the extent observed.

The remobilization of low temperature sulfides in a sulfide melt is consistent with their distribution in low pressure zones (such as veins and boudins) and a lack of aqueous liquid-bearing secondary inclusions. Moreover, the crystallization of sulfides from a melt is unaffected by their high solubility in hydrothermal fluids, and is compatible with the contrasting  $fS_2$  conditions required to form realgar and native arsenic (or stibnite and native antimony) in the same rock.

## The role of hydrothermal fluids

Post-peak metamorphic fluid infiltration at Hemlo is evident from irregularly distributed calc-silicate and sericitic alteration assemblages, which occur in relatively undeformed veins and fractures that cross-cut the ore zones and host lithologies. Ore zone rocks locally show evidence of alteration by calc-silicate mineral assemblages, sericite and assemblages containing both calc-silicate minerals and sericite. This suggests that late-stage alteration formed either in an evolving hydrothermal system, or that the different assemblages reflect differences in the lithologies with which fluids equilibrated. The importance of this late-stage hydrothermal event for gold mineralization is strongly debated. Pan and Fleet (1992; 1995) interpreted calc-silicate-related alteration to have been associated genetically with the main stage of gold mineralization. By contrast, other studies consider that it was largely unrelated to mineralization (e.g., Kuhns, 1988; Williams-Jones et al., 1998; Muir, 1997, 2002; Heiligmann et al., Chapter 4).

Calc-silicate alteration is clearly post-peak metamorphic, and is not associated with primary mineralization. These alteration zones also occur beyond the confines of the deposit where they are not mineralized (e.g., Muir, 1997). Gold intergrown with calc-silicate mineral assemblages is compositionally similar to that associated with demonstrably pre-peak metamorphic molybdenite and post-peak metamorphic remobilized low temperature sulfides (Williams-Jones et al., 1998), suggesting that calc-silicate-related gold was remobilized from primary mineralization. Finally, contrary to Pan and Fleet (1992), who reported the presence of primary fluid inclusions, all fluid inclusions in gold-related quartz in ore zone rocks occur on fracture planes and are therefore secondary. No characteristics unambiguously diagnostic of primary inclusions, such as their occurrence in growth zones, were observed during this study, despite examination of an extensive sample suite.

Ore zone rocks contain large numbers of secondary fluid inclusions, especially in quartz veins and boudins, and locally in late-stage calc-silicate alteration zones. The most abundant fluid inclusion type is liquid-only (~85 % of all inclusions), but liquidvapor (~10 %), liquid-vapor-solid (interpreted to be halite based on cubic shape; ~5%), and very rare CO<sub>2</sub>-only and liquid-vapor inclusions with two translucent solids were also observed. Liquid-vapor and liquid-vapor-solid inclusions locally contain low temperature sulfide minerals, such as realgar, orpiment and cinnabar. However, as was noted earlier, such inclusions were found only where fluid and solid inclusion trails intersect, and the lack of consistency in the proportions of the sulfides relative to liquid and vapor in the inclusions suggests that they are not daughter minerals but trapped phases (either liquid or solid). This indicates that hydrothermal alteration at Hemlo generally post-dated remobilization of gold by a sulfide melt.

Fluid inclusion homogenization temperatures ( $T_h$ ) range from ~90 to 350°C (Fig. 5-6), with a peak at 150 to 200°C. Liquid-vapor inclusions have the largest  $T_h$  range (from ~95 to 350°C), whereas liquid-vapor-solid, liquid-vapor-2 solids and liquid-vapor-sulfide inclusions have  $T_h$  values between ~125 and 200°C. Interestingly, the observed  $T_h$  mode for these secondary inclusions is similar to that reported by Pan and Fleet (1992) for inclusions which they interpreted to be primary (they also found rare inclusions with  $T_h$  up to ~450°C).

Figure 5-6.

Frequency distribution of homogenization temperatures of fluid inclusions. All fluid inclusions are secondary and considered to represent late-stage fluid infiltration that occurred during retrograde cooling of the Hemlo ore zones.



Fig. 5-6

The fluid inclusion evidence presented here shows clearly that remobilization of gold by hydrothermal fluids responsible for calc-silicate alteration was a comparatively late-stage phenomenon. Moreover, the fact that in a study of the distribution of gold grains, Williams-Jones et al. (1998), reported none in contact with calc-silicate minerals, versus 19 in contact with low temperature sulfides (see below), suggests that only minor gold was reconcentrated by this event.

#### Phase relations in the system As-Sb-S

The temperatures of crystallization of individual minerals or mineral assemblages in the system As-Sb-S are difficult to evaluate as data on their thermal stability are only available for a pressure of 1 bar. However, as melting generally involves an increase in volume, the temperature at which most minerals melt is likely to increase with increasing pressure (cf., Frost et al., 2002). For example, the temperature of the eutectic for the assemblage FeS-PbS-ZnS increases by 6°C/kb (Mavrogenes et al., 2001) and the temperature at which the reaction arsenopyrite + pyrite = melt + pyrrhotite occurs increases by 17 °C/kb (Clark et al., 1960; Frost et al., 2002). On the other hand, the temperature at which native antimony melts decreases by 0.2 °C/kb (Liu and Basset, 1986). In contrast to pressure, the addition of substitutions generally decreases the melting temperature as they typically partition preferentially into the melt and thus expand its field of stability to lower temperature. Therefore in the subsequent discussion all temperatures are reported for 1 bar pressure and are assumed to represent the approximate temperatures of crystallization.

Experimental studies of the As-Sb-S system indicate that at the peak metamorphic temperatures for Hemlo (~630°C), almost any bulk composition in the system would have been molten (Fig. 5-7). At ~630°C, two immiscible sulfide melts coexist, one close to the Sb-S join, and the other occupying the central portion of the diagram (Craig et al., 1974; but this study did not constrain the exact location of immiscible melts in the As-Sb-S system). This immiscibility may explain the occurrence, at Hemlo, of abundant, coarse-grained stibnite along grain boundaries and the lack of low-temperature sulfides intergrown with stibnite. Stability relations in the system indicate that the assemblage stibnite-pääkkönenite-native antimony (or stibarsen)  $\pm$ native arsenic formed at relatively high temperature (~500 to 550°C) from a melt occupying the central portion of the As-Sb-S system. As the deposit continued to cool, the melt became progressively enriched in As (and S) and crystallized the assemblages stibnite-realgar, stibnite-orpiment and stibnite-wakabayashilite-realgar (Fig. 5-8).

The occurrence of individual stibnite grains and the assemblages stibnitepääkkönenite-native antimony and native antimony-stibarsen, or minerals such as native arsenic on grain boundaries is consistent with a predominantly ductile setting during amphibolite-facies temperatures and pressures (Fig. 5-8). Lower temperature assemblages, such as those that contain realgar are common as secondary inclusions, and are indicative of an environment in which deformation was largely brittle. The widespread occurrence of these As-Sb-S and related minerals at Hemlo is consistent with their crystallization from a relatively homogeneous melt that formed at P-T conditions close to those of peak metamorphism. If this interpretation is correct, then Figure 5-7.

Isothermal sections showing phase relations in the As-Sb-S system at 630, 500, 400 and 250°C. At 630°C, the melt field (grey) covers almost the entire diagram, and at low temperatures shrinks progressively until the final melt is located near the As-S join. Figure A was constructed from phase relations and upper thermal stabilities in the system; Figure B was modified from Luce et al. (1977) and Craig et al. (1974); Figures C and D were modified from Bernardini et al. (1992).



Fig. 5-7

Figure 5-8.

Evolution of mineral assemblage in the As-Sb-S system during cooling. Higher temperature assemblages occur predominantly on grain boundaries, while late phases make up most of the solid inclusions, consistent with brittle fracturing at lower temperature. Note that the low temperature assemblages on secondary inclusion trails may have been trapped at higher temperatures than those suggested by the upper thermal stabilities of the minerals.



the low temperature sulfide assemblages are the products of fractional crystallization of a sulfide melt that cooled several hundred degrees before solidifying. However, it is also likely that some pockets of melt were isolated during the crystallization process, which may explain the large number of low temperature sulfide minerals present at Hemlo.

## Remobilization of gold by sulfide melt

Gold in the Hemlo ore zones can be subdivided into two types based on its mode of occurrence: (a) primary gold, which is commonly associated with molybdenite and potassic alteration minerals; and (b) remobilized gold, which occurs with relatively low-temperature minerals (such as stibnite and realgar), and is concentrated in extensional features such as veins and boudins. The association of primary gold with molybdenite is consistent with the correlation factor of 0.58 for Au and Mo in bulk rock samples containing more than 1 ppb Au (Fig. 5-9). Remobilized gold crystallized mainly as Hg-bearing native gold and occasionally aurostibite, and rarely as gold tellurides (such as calaverite). This gold occurs frequently with stibnite (Fig. 5-3), suggesting crystallization from a Sb-S dominated immiscible melt (in the As-Sb-S system) at temperatures of ~550-500°C, and is consistent with the correlation coefficient of 0.49 for Au and Sb in bulk rock samples containing more than 1 ppb Au (Fig. 5-10) By contrast, arsenic-bearing sulfides are less commonly in contact with native gold, indicating that the As-S-dominated, late stage melt contained only minor concentrations of gold.

Figure 5-9.

Comparison of Au and Mo bulk rock compositions for Hemlo rocks containing more than 1 ppb Au. Molybdenite, the main host of Mo, is genetically associated with primary mineralization, which is supported by the positive correlation (0.58) of Au with Mo.



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Figure 5-10.

Comparison of Au and Sb bulk rock concentrations at Hemlo. The common association of stibnite and native gold is consistent with the positive correlation of 0.49 of Au with Sb.



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Aurostibite coexists with calaverite (AuTe<sub>2</sub>) and with both native gold and antimony. Calaverite, formed as temperature decreased below ~464°C (Fig. 5-11). Phase relations in the Au-Sb system (data are available only for 1 bar) indicate that the assemblage aurostibite+native antimony formed below ~460°C and aurostibite+native Au below ~360°C (Fig. 5-12). Assuming a relatively small correction of temperature for pressure, these mineral associations indicate that gold crystallized from the melt throughout much of the retrograde cycle.

Remobilized native gold is generally much coarser-grained than primary native gold associated with molybdenite, and, frequently, yields the highest gold grades (in stibnite-rich zones). The distribution of gold grains on a section through the Golden Giant deposit was investigated by Williams-Jones et al. (1998), who found that out of 128 native gold grains, 73 were in contact with K-feldspar and molybdenite, whereas 17 were in contact with stibnite and realgar (the remaining 38 grains were associated with minerals such as barite and quartz and could be either primary or secondary; none were in contact with calc-silicate minerals). Considering that the K-feldspar-molybdenite association is indicative of primary mineralization, and stibnite and realgar crystallized from a post-mineralization sulfide melt, we estimate that ~25 % of the mineralization at Hemlo was remobilized by the melt.

#### Sulfide melt source

A reliable interpretation of sulfide melt formation requires that the temperature of primary mineralization be broadly known. If the latter occurred at relatively low temperature (e.g., epithermal conditions, T<300°C), stibnite, arsenopyrite and/or

Figure 5-11.

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Phase relationships in the Au-Te system. Calaverite forms at 464°C and the assemblage calaverite + native Au below 447°C (modified from Okamoto and Massalski, 1986a).



Fig. 5-11

Figure 5-12.

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Phase relations in the Au-Sb system (Okamoto and Massalski, 1986b). The phase relations indicate that the assemblage aurostibite + native Sb formed at T<460°C, and aurostibite + native Au at T<360°C.



wt % Sb

Fig. 5-12

realgar could have formed initially, and then melted as the prograde metamorphic temperature exceeded the upper limit of their thermal stability. However, the geology of the Hemlo deposit is inconsistent with an epithermal origin. For example, with the exception of the remobilized ore, mineralization is diffuse or disseminated, and is not hosted by veins or breccias. This style of mineralization cannot be explained by invoking dissolution of carbonates (as in Carlin-type deposits) or acid-sulfate alteration (as in high-sulfidation deposits) as there is evidence for neither. Rather it calls for the passage of fluids through rock undergoing deformation in a dominantly ductile regime (i.e., at much greater depth than interpreted for the formation of epithermal deposits). In addition, the strong enrichment of molybdenum, the focussed structural control of alteration, and the preservation of sulfide melt through the brittle stages of prograde metamorphism, are inconsistent with mineralization at low temperature and/or shallow crustal levels (Heiligmann et al., Chapter 4). On the contrary, the structural shear zone setting and occurrence of mineralization during regional metamorphism, the high concentrations of elements such as Mo, Sb, As, Hg, W and Te, the lack of base metals, and the pervasive potassic alteration, support a mesothermal-orogenic model involving a significant magmatic fluid component (Heiligmann et al., Chapter 4). At the inferred mineralization conditions (400 to 500 °C, 3 to 5 kb; Heiligmann et al., Chapter 4), most As- and Sb-bearing minerals are either above their upper thermal stability (e.g., realgar), or are extremely soluble (e.g., stibnite), and are therefore unlikely to have precipitated from a hydrothermal fluid. Tomkins et al. (2004) proposed that arsenopyrite was the source of As in the sulfide melt. However, although minor arsenopyrite occurs in the altered hangingwall rocks,

it is conspicuously absent from the ore zone. Moreover, at the high  $fS_2$  conditions of primary gold mineralization (evident from the presence of pyrite; Heiligmann et al., Chapter 2) the solubility of arsenopyrite at ~450°C is too high (>10000 ppm) for this mineral to have precipitated (Heiligmann et al., Chapter 4). At lower  $fS_2$  conditions, such as those coinciding with the pyrrhotite stability field, and occurring near the margins of the deposit, arsenopyrite is less soluble and theoretically could have precipitated from a hydrothermal fluid. This gradient in  $fS_2$  conditions (high in the ore zones and lower near the margins of the deposit) is supported by higher Fe concentrations in biotite, the appearance of pyrrhotite, and the occurrence of Febearing metamorphic index minerals such as garnet and staurolite with increasing distance from the mineralization (Heiligmann et al., Chapter 2). These facts suggest that arsenopyrite did not form during the main mineralization event, and is thus unlikely to have been a source of As for the sulfide melt. (Tomkins et al. (2004) also proposed that stibnite was the source of Sb in the melt, which as discussed above, is unlikely to have saturated in a hydrothermal fluid at the temperature of mineralization.)

An alternative, which we favor, is that As and Sb were initially hosted by pyrite and were released by recrystallization during peak metamorphism. The occurrence of As- and Sb-bearing pyrite in gold deposits is well documented (e.g., Cook and Chryssoulis, 1990; Arehart et al., 1993; Fleet et al., 1993; Tanocai et al., 1997; Ashley et al., 2000; Hofstra and Cline, 2000; Pals et al., 2003), and pyrite is known to accommodate a wide variety of trace metals (As, Sb, Tl, Pb, Cu, Hg and Au) in its lattice. Incorporation of such elements occurs through the distortion of the pyrite

structure due to the substitution of As (and possibly Sb) for S, which permits the substitution of other elements for Fe (e.g., Griffin et al., 1991; Arehart et al., 1993; Fleet et al., 1993; Tarnocai et al., 1997). During metamorphic recrystallization, these elements are exsolved (e.g., Mumin et al., 1994; Larocque et al., 1995; Tarnocai et al., 1997), and since pyrite is by far the most abundant sulfide mineral at Hemlo ( $\sim$ 5 wt% pyrite, compared to 311 ppm Sb and 211 ppm As), substitutions of  $\sim$ 1 % combined As and Sb would be sufficient to account for the observed bulk rock concentrations of these elements. It should also be noted that sulfides have notoriously high diffusion coefficients, so that reaction between melt and residual sulfides is likely to be very efficient (Frost et al., 2002). For example, Clark et al. (1960) noted that Au diffuses readily out of arsenopyrite and into the melt.

Although we propose that the sulfide liquid formed primarily from elements exsolved from pyrite, melting of primary minerals is also likely to have contributed to the formation of this liquid. However, the importance of the latter is difficult to evaluate, since, once melted, these minerals are generally absent from the deposit. Nevertheless, there are some exceptions. Native gold contains significant concentrations of Hg (avg. 6 at.%, max 15 at.%; Williams-Jones et al., 1998), which lowered its thermal stability (because the Hg partitions preferentially into the melt phase). Experiments indicate that gold containing 15 at.% Hg starts melting at ~  $500^{\circ}$ C (Fig. 5-13). This suggests that some Hg-rich primary gold probably melted during peak metamorphism. Other possible candidates for melting are tennantite (Cu<sub>12</sub>As<sub>4</sub>S<sub>13</sub>) and tetrahedrite (Cu<sub>12</sub>Sb<sub>4</sub>S<sub>13</sub>), which, when pure, melt at >650°C. At Hemlo, these minerals also contain significant Zn, Hg, and Ag, which would have

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Figure 5-13. Phase relations in the Au-Hg system (Okamoto and Massalski, 1989). Native gold at Hemlo contains up to 15 at.% Hg and would have melted at the temperature of peak metamorphism (~630°C)





Fig. 5-13

)

lowered their upper thermal stability. For example, Zn-rich tennantite  $(Cu_{12}Zn_2As_4S_{13})$  or tetrahedrite  $(Cu_{12}Zn_2Sb_4S_{13})$  may melt at temperatures as low as ~ 450°C (Seal, 1990). At Hemlo, tennantite-tetrahedrite contains up to 8 wt% Zn, suggesting that it may well have undergone melting.

## The role of metamorphic fluids

Although we believe that the sulfide melt formed predominantly from elements exsolved by pyrite during peak metamorphism and to a lesser extent from primary orerelated minerals, interstitial aqueous fluids also likely played a role in the melting process. Metasedimentary rocks, that comprise the main precursor lithologies for the ore zone rocks, release water during prograde metamorphism, and it is therefore probable that Hemlo rocks still contained some interstitial water during peak metamorphism. As pyrite recrystallized, but did not transform to pyrrhotite, the aS2 of the interstitial fluid must have been relatively high during peak metamorphism, which rules out an open system in which important quantities of fluid percolated through the ore zones (Heiligmann et al., Chapter 2). We propose that, although elements such as Sb and As are very soluble at elevated temperature, the small quantities of available water allowed these elements to saturate and form a sulfide melt (since they could not have formed minerals at these temperatures). Once this melt was created, it preferentially incorporated chalcophile elements (including sulfur). In addition, the melt incorporated elements exsolved from pyrite, and melted primary minerals such as Hg-bearing native gold. The co-existence of a sulfide melt with a hydrothermal fluid was also postulated for the Lengenbach polymetallic deposit, Switzerland (Hoffmann,

1994), where the slow cooling and fractional crystallization of a melt-aqueous fluid system led to the formation of at least 22 sulfide mineral species. At Hemlo, the surprising homogeneity of the melt (it crystallized the same As-Sb-S minerals throughout the deposit) and its mobility within the ore zones (melt migrated into folds, boudins, quartz veins) are further support for the initial co-existence of an aqueous phase and an immiscible sulfide melt.

## Liquid line of descent

Our proposed liquid line of descent for crystallization of the sulfide melt at Hemlo is based on a theoretical evaluation of the As-Sb-S system, textural and paragenetic relationships of As-Sb-S-bearing mineral assemblages with more complex sulfides and sulfosalts, phase relations in corresponding systems, and the upper thermal stability of these assemblages (Fig. 5-14).

Based on theoretical relationships, the first minerals to crystallize from a cooling sulfide melt in the Pb-Sb-S system are boulangerite, robinsonite, zinkenite and stibnite (at T>550°C). These minerals are present in Hemlo ore zone rocks, and occur primarily on grain boundaries, which are interpreted to have accumulated most of the high temperature remobilized minerals. In addition, stibnite and zinkenite are frequently intergrown, suggesting contemporaneous crystallization (Fig. 5-15). Within the As-Sb-S system, the highest temperature assemblages are stibnite $\pm$ native Au and pääkkönenite-stibnite-native antimony ( $\pm$  native As), which become stable between ~550 and 500°C. These minerals were the first phases to crystallize from the two immiscible melts which formed in the As-Sb-S system at peak metamorphic

Figure 5-14.

Proposed liquid line of descent for mineral assemblages precipitated from a sulfide melt at Hemlo. Polymetallic melt is generated during peak metamorphism and crystallized progressively during cooling. Initially, the melt was dominated by Sb+As+S and contained minor concentrations of Cu, Hg, and Pb, whereas the final melt contained mostly As+S.



Figure 5-15.

Phase stability relationships in the Pb-Sb-S system as a function of temperature and composition. Zinkenite and stibnite form a relatively common assemblage at Hemlo, whereas boulangerite and robinsonite are rare. Modified from Salanci, 1979; Chang and Bever, 1973, and Craig, Chang and Lees, 1973)


Fig. 5-15

conditions. Tetrahedrite is the most common Cu-bearing phase in the deposit, and depending on its composition, crystallized from ~610 to 460°C. Locally, tetrahedrite is intergrown with the assemblage pääkkönenite-stibnite-native Sb, suggesting formation between ~550 and 500°C. As temperature decreased from ~500 to below 300°C and the As-Sb-S system evolved towards more As-rich compositions, stibnite-realgar, stibnite-realgar-wakabayashilite ((As,Sb)<sub>11</sub>S<sub>8</sub>), getchellite (AsSbS<sub>3</sub>), orpiment and realgar became stable. These minerals are intergrown locally with cinnabar and native gold. Cinnabar is stable over a wide range of temperature (up to ~800°C as meta-cinnabar), but at Hemlo is frequently intergrown with realgar, which constrains its crystallization temperature to below ~315°C. Gudmundite (FeSbS) has an upper thermal stability of ~280°C and is locally associated with aurostibite, which suggests that the sulfide melt crystallized gold-bearing phases throughout most of the retrograde cycle. These relationships summarize the fractional crystallization path of the complex Sb-As-Cu-Pb-Hg-bearing sulfide melt responsible for the distribution of low-T minerals and remobilized gold at Hemlo.

#### Sulfide melts and remobilized gold

The formation of sulfide melts has not been a popular remobilization mechanism for metamorphosed ore deposits (e.g., Marshall and Spry, 2000). One of the first to posit such melting was Lawrence (1967), who suggested that metamorphism of the Broken Hill Pb-Zn-Ag deposit of New South Wales, Australia, produced a partial melt. Although later studies by Plimer (1987) and Skinner and Johnston (1987) expressed doubts that significant melt formed and consequently that there was much remobilization, recent experimental studies by Mavrogenes et al. (2001) suggest that melting did play an important role in the evolution of the deposit. Other deposits for which remobilization of sulfide melts may have been important include Bleikvassli (Zn-Pb-Cu) in Norway (Vokes, 1971), Lengenbach (Pb-Zn-As-Tl-Ba), Switzerland (Hoffmann, 1994; Hoffmann and Knill, 1996; Knill, 1996), and Challenger (Au) in Australia (Tomkins and Mavrogenes, 2002). Despite the small number of studies that have invoked metamorphism-induced sulfide melting, recent work suggests that such melting may be more common than previously thought (e.g., Frost et al., 2002). Considering that melting was overlooked in a well-studied deposit such as Hemlo for almost two decades, it appears likely that this process also occurred in many other deposits in high grade metamorphic terrains.

The potential distance of remobilization is still uncertain; at Hemlo, melt migration occurred on a cm to m scale but did not extend significantly outside the ore zones. However, it is conceivable that sulfide melts could migrate over substantial distances in cases where large scale deformation occurs synchronously with peak metamorphism. Finally, the association of low temperature sulfide minerals such as realgar, orpiment and stibnite with gold in high-grade metamorphosed terrains has important implications for mineral exploration, as these assemblages may represent remobilized segments of larger orebodies.

#### Conclusions

Distinguishing between primary and remobilized mineralization in metamorphosed ore deposits, such as Hemlo, is complicated by metamorphic overprints that destroy most primary mineralization features. Remobilization may occur through a variety of processes including late stage hydrothermal alteration and the generation of sulfide melts, but the scale and extent of these mechanisms is often difficult to determine. At Hemlo, late-stage hydrothermal fluid infiltration created calc-silicate and sericitic alteration zones, which locally contain remobilized gold. However, the limited extent of this type of alteration, and the fact that it is commonly unmineralized, indicates that late-stage hydrothermal fluid infiltration represents only a secondary and relatively unimportant remobilization mechanism.

Although melting of sulfide assemblages has only rarely been proposed to play a significant role in ore metal remobilization, it is the most plausible explanation for the occurrence and distribution of low temperature ore-related sulfide minerals at Hemlo. The abundance and distribution of low temperature sulfides such as realgar, orpiment, zinkenite and stibnite, the absence of hydrothermal liquid in solid inclusion trails, the extremely high solubility of minerals such as stibnite at temperatures above 300 °C, and the evidence of contrasting  $fS_2$  conditions (e.g., native As and Sb with realgar and stibnite), are inconsistent with hydrothermal remobilization, but compatible with fractional crystallization of a sulfide melt.

The main mineralization event at Hemlo is interpreted to have occurred at a temperature of 400 to 500°C and was followed by the formation of a sulfide melt near peak metamorphic conditions (630°C) and its crystallization during retrograde cooling. The sulfide liquid formed through the exsolution of elements such as As and Sb from pyrite during metamorphic recrystallization, the melting of primary ore minerals, and the interaction of melt with aqueous metamorphic fluids carrying sulfur.

The association of native gold with stibnite and realgar, and the wide range of upper thermal stabilities of calaverite, aurostibite + native antimony, and aurostibite + native gold assemblages also observed at Hemlo, indicate that gold was remobilized over an extended interval of temperature; from at least 550°C to below 300°C.

Mineralogical data from solid inclusions show that the melt was composed primarily of As, Sb and S, with minor but significant concentrations of Cu, Pb, Hg and Au. During retrograde metamorphic cooling, the sulfide liquid crystallized progressively from a temperature close to that of peak metamorphism (e.g., stibnite at ~550°C) until temperature dropped below ~300 °C, at which point the remaining melt was largely dominated by As and S and formed realgar and orpiment. The mineral assemblages are generally consistent with fractional crystallization from an As-Sb-S dominated melt, and define a liquid line of descent that started with the sulfosalts, boulangerite, robinsonite and stibnite ( $\pm$  native gold) and terminated with orpiment, realgar ( $\pm$  native gold) and gudmundite.

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# Chapter 6

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# **Conclusions and Summary**

### **Conclusions and summary**

Regional metamorphism overprinted the Hemlo gold deposit, recrystallized the alteration zones, and obscured timing relationships. In large part, this is the reason why there has been little agreement on the origin of the mineralization.

Metamorphic index minerals are absent from the altered metasediments that host most of the Au mineralization because these minerals are not stable in the presence of the sulfide-sulfate-silicate-oxide assemblage. During peak metamorphism, the ore zone assemblage, biotite-muscovite-microcline-quartz, recrystallized but did not form the index minerals normally expected in amphibolite-facies rocks. Their absence is therefore non-diagnostic of peak metamorphic conditions and misleading as to the timing of mineralization with respect to metamorphism. Multiple generations of metamorphic index minerals (such as garnet, staurolite and aluminosilicates) in the Hemlo area outside the ore zones are consistent with a single metamorphic cycle of prograde and retrograde metamorphism. The occurrence of these minerals is interpreted to have resulted from the presence of normal ('Barrovian') and 'high-Al, low Fe+Mg' metapelites, that crystallized index minerals in different sequences (i.e., Barrovian metapelites form these minerals in the order: biotite, garnet, staurolite, kyanite/sillimanite, whereas 'high-Al, low Fe+Mg' pelites form early kyanite, staurolite, garnet, biotite, late kyanite/sillimanite). In addition, local sulfidation of 'high-Al, low (Fe+Mg)' metapelites preserved early, low temperature kyanite by partitioning Fe into pyrite, thereby preventing the normal evolution of these rocks.

Geothermobarometric data for metapelites and metabasites indicate that peak metamorphic conditions reached ~630°C and 5 to 7 kb, and coincided with the formation of sillimanite, which is the mineral associated with the highest temperatures at Hemlo. As sillimanite is aligned in S2 and S3 (e.g., Muir and Elliot, 1987), peak (thermal) metamorphism likely occurred either during the late-D2 or D3 stage of deformation.

Mineralization occurred prior to peak metamorphism at greenschist facies conditions (400 to 500°C) through a decrease in pH and  $fO_2$  in the pyrite stability field. Thermodynamic modeling indicates that these changes resulted mainly from potassic alteration, precipitation of pyrite, and dissolution of barite. Geological and geochemical characteristics (narrow structural control, finely disseminated mineralization, enrichment in As, Sb, Mo and K, lack of Cu) are consistent with a mesothermal-orogenic model for the genesis of the Hemlo deposit that includes an important magmatic component in the ore fluid.

During peak metamorphism, mineralization was extensively remobilized by the formation of a sulfide melt, which crystallized during retrograde cooling. The sulfide melt formed through the exsolution of elements such as As and Sb from pyrite during metamorphic recrystallization, the decomposition of primary ore minerals, and the interaction of melt with aqueous metamorphic fluids carrying sulfur. Mineralogical data from solid inclusions indicate that the melt was composed primarily of As, Sb and S, but included significant concentrations of Cu, Pb, Hg and Au. During retrograde metamorphic cooling, the sulfide liquid crystallized progressively from a temperature close to that of peak metamorphism (e.g., stibnite at ~550°C) until temperature dropped below ~300 °C, at which point the remaining melt was largely dominated by As and S,

and formed realgar and orpiment. The association of native gold with stibnite and realgar, and the wide range of upper thermal stabilities of calaverite, aurostibite + native antimony, and aurostibite + native gold, assemblages also observed at Hemlo, indicate that gold was remobilized over an extended interval of temperature; from at least 550°C to below 300°C.

#### **Contributions to knowledge**

This thesis makes a major contribution to our understanding of the origin of the Hemlo gold deposit, and to that of metamorphosed gold mineralization in general. Prior to this study, and despite its importance as one of Canada's major gold producers, almost every aspect of the Hemlo gold deposit has provoked disagreement. For example, the relative timing of mineralization has been interpreted as pre-, syn- or post-peak metamorphism, interpretations of regional metamorphism have included multiple prograde events and peak temperatures that varied between 500 and 650°C, and the genesis of the deposit had been variably explained in terms of epithermal, porphyry, skarn, and mesothermal genetic models. This study reconciles most issues of contention in previous studies and presents a genetic model that satisfactorily explains all of the significant features of the deposit.

#### Sulfide-sulfate-silicate-oxide equilibria

This is the first study to model sulfate-sulfide-oxide-silicate equilibria in mesothermal gold deposits. Sulfidation-oxidation reactions have mostly been evaluated

for base metal massive sulfide deposits, as gold-rich systems generally do not contain enough sulfur for large-scale sulfidation. However, the extensive occurrences of sulfate (barite) at Hemlo increased the amount of available sulfur in the mineralizing environment, and significantly influenced the evolution of ore zone rocks during metamorphism. The dissolution of barite provided Ba for silicate alteration minerals, and increased the stability of pyrite by raising  $fS_2$ . Pyrite in turn fixed Fe, which was thus unavailable to participate in prograde metamorphic reactions.

#### Index mineral paradox

The lack of metamorphic index minerals at Hemlo has previously been interpreted as evidence for a post-peak metamorphic timing of mineralization. This study demonstrates that minerals such as garnet, staurolite and aluminosilicates can only form near the margins of the deposit, and are not in equilibrium with the sulfate-sulfide-oxidesilicate assemblage that predominates in most of the ore zones. Mineral assemblages in the deposit, therefore, are not indicative of the metamorphic grade, and textural relationships among metamorphic minerals adjacent the ore zones differ from those observed in normal pelites (i.e., early kyanite is preserved near the margins of the deposit due to the sulfidation overprint.).

#### A new genetic model for Hemlo

The origin of the Hemlo gold deposit has long been contentious as is evident from the large number of proposed depositional models, none of which have satisfactorily explained all features of the deposit (e.g., structural setting of the mineralization, strong enrichment in Mo and K, and association of the ore with stibnite and realgar). These features are, however, readily explained by the mesothermal mineralization model presented in this thesis, which invokes a mixed metamorphic-magmatic ore fluid. As the origin of the mineralizing fluids for mesothermal deposits has probably been the most debated issue for this class of deposits, conclusions for Hemlo have broader implications. Many mesothermal gold deposits have recently been termed 'orogenic', and were interpreted to form from predominantly metamorphic fluids. The proposal made in this thesis, that structurally-hosted, magmatic-hydrothermal and metamorphic deposits represent endmembers of a single deposit class, would explain the contrasting alteration styles, wide range of element enrichments and the occurrence of 'anomalous' deposits such as Hemlo and Hollinger-McIntyre.

#### The importance of timing relationships

Most mesothermal deposits are thought to form during greenschist-facies conditions after peak metamorphism. However, only a small number of occurrences in amphibolite- and granulite-facies rocks have been described, and their timing relationships are often poorly established. Hemlo is therefore an important 'case-study' for the less typical conditions under which mesothermal/orogenic deposits form.

#### Melting of ore deposits

Although melting of sulfide assemblages has rarely been proposed as a remobilization process, it is the most plausible explanation for the distribution of low temperature, sulfide minerals at Hemlo. The abundance and distribution of low temperature sulfides such as realgar, orpiment, zinkenite and stibnite, the absence of hydrothermal liquid in solid inclusion trails, the high solubility of minerals such as stibnite at temperatures above 300 °C, and the evidence of contrasting  $fS_2$  conditions (e.g., native As and Sb with realgar and stibnite), are inconsistent with hydrothermal remobilization, but compatible with their crystallization from a sulfide melt.

The multistage process proposed in this thesis is consistent with the mineralization model derived for Hemlo, and may very well apply to other important ore deposits in high-grade metamorphic terranes. As remobilization of gold by a sulfide melt was overlooked at Hemlo, a very well-studied ore deposit, it is very likely that this process may be much more important then previously thought.

# Appendix I

## Electron microprobe analyses of metapelites

### Hemlo Garnet Probe Data

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 20 nA; 20 s peak counts; 5 um beam. Total Fe as FeO. Lower detection limits at 2SD are 0.01-0.02 wt %.

Orthoclase-, albite, spessartine, gamet, TiO2 and diopside-based standards for all major elements.

Plagioclase analyses for amphibole-plagioclase geothermometry.

Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO₂	Cr <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Total
	%	%	%	%	%	%	%	%	%	
T226-8-1	36.77	20.83	0.05	0.02		34.47	2.73	3.51	0.88	99.26
T226-8-2	36.38	20.86	0.00	0.01		34.99	2.79	2.86	1.02	98.89
T226-8-3	36.71	20.81	0.02	0.03		34.84	2.92	3.43	0.64	99.39
T226-8-4	36.64	21.01	0.01	0.00		34.91	3.10	3.18	0.85	99.70
T226-8-5	36.66	20.72	0.02	0.02		34.70	2.42	3.34	1.20	99.08
T226-8-6	36.41	20.55	0.00	0.00		34.61	2.24	3.30	1.22	98.34
T226-8-7	36.59	20.83	0.03	0.01		34.10	2.65	3.58	1.22	99.01
T226-8-8	36.67	20.87	0.03	0.00		33.43	2.85	4.36	0.77	98.97
T226-175-1	37.03	20.89	0.08	0.05		29.41	4.01	3.01	4.94	99.41
T226-175-2	36.93	21.19	0.06	0.05		29.59	3.76	2.79	5.10	99.46
T226-175-3	37.02	21.19	0.07	0.09		30.43	4.42	2.73	3.86	99.80
T226-175-4	36.76	21.12	0.06	0.06		30.08	4.39	2.64	3.84	98.94
T226-175-5	36.96	21.09	0.08	0.15		28.68	4.53	3.06	4.87	99.42
T226-175-6	36.96	21.22	0.01	0.00		28.83	4.68	2.96	4.50	99.16
T226-175-(2)-1	36.58	21.15	0.05	0.06		30.54	4.26	2.28	4.02	98.93
T226-175-(2)-2	36.93	21.16	0.02	0.01		30.38	4.25	2.36	4.06	99.18
T226-175-(2)-3	36.70	20.94	0.00	0.01		30.20	3.84	2.18	4.85	98.73
T226-175-(2)-4	37.00	21.38	0.04	0.00		30.87	5.06	2.47	2.60	99.41
T226-175-(2)-5	36.97	21.16	0.03	0.07		30.70	5.01	2.41	2.96	99.28
T226-175-(3)-1	36.75	21.10	0.07	0.13		30. <del>94</del>	4.54	2.36	3.43	99.32
T226-175-(3)-2	36.72	21.04	0.03	0.09		30.55	4.27	2.55	3.94	99.18
T226-175-(3)-3	37.12	21.32	0.03	0.07		30.81	5.49	2.44	1.97	99.25
T226-175-(3)-4	37.37	21.49	0.05	0.05		30.72	5.51	2.33	2.12	99.64

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Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Totai
	%	%	%	%	%	%	%	%	%	
T226-175-(3)-5	37.10	21.38	0.04	0.00		30.71	5.43	2.30	2.43	99.39
T226-175-(3)-6	37.08	21.24	0.04	0.03		30.46	5.33	2.34	2.61	99.13
T226-175-(3)-7	37.09	21.22	0.02	0.04		30.08	5.31	2.62	2.67	99.05
T226-175-(3)-8	37.12	21.30	0.01	0.00		29.96	5.13	2.64	3.22	99.37
T226-175-(3)-9	37.09	21.23	0.06	0.04		<b>29.88</b>	4.92	2.56	3.70	99.46
T226-175-(3)-10	36.96	21.12	0.03	0.00		29.17	4.86	2.66	4.35	99.14
T226-175-(3)-11	37.15	21.14	0.07	0.00		29.07	4.53	2.75	5.12	99.82
T226-175-(3)-12	36.96	21.04	0.08	0.05		28.02	4.24	2.81	6.14	99.33
T226-175-(3)-13	36.57	20.91	0.11	0.04		27.68	3.93	2.82	6.62	98.68
T226-175-(3)-14	36.79	20.88	0.08	0.09		27.77	3.99	2.77	6.71	99.08
T226-175-(3)-15	37.02	20.99	0.35	0.05		27.90	3.99	2.52	6.43	99.26
T226-175-(3)-16	36.93	21.19	0.05	0.00		28.01	4.12	2.70	6.29	99.29
T226-175-(3)-17	36.70	21.15	0.06	0.05		28.48	4.32	2.60	5.59	98.95
T226-175-(3)-18	37.03	21.35	0.02	0.00		29.68	4.98	2.76	3.62	99.46
T226-175-(3)-19	37.18	21.26	0.00	0.00		30.15	5.11	2.54	3.08	99.32
T226-175-(3)-20	37.05	21.10	0.06	0.00		30.31	4.53	2.27	3.77	99.09
T226-175-(3)-21	36.96	21.14	0.06	0.03		30.70	4.48	2.24	3.88	99.49
970720-5-(1a)-1	36.98	21.04	0.01	0.01		33.47	3.82	3.49	0.58	99.39
970720-5-(1a)-2	36.88	21.04	0.01	0.00		33.45	3.71	3.43	0.68	99.20
970720-5-(1a)-3	37.04	21.08	0.04	0.00		33.52	3.26	3.65	0.94	99.54
970720-5-(1a)-4	36.81	20.96	0.00	0.03		33.81	3.62	3.30	0.72	99.24
970720-5-(1a)-5	36.97	20.87	0.00	0.03		33.3 <del>9</del>	3.71	4.12	0.27	99.34
970720-5-(1a)-6	36.87	20.93	0.02	0.02		33.12	3.67	4.38	0.20	99.20
970720-5-(1b)-1	36.62	20.96	0.04	0.00		33.91	3.78	3.28	0.66	99.25
970720-5-(1b)-3	36.74	20.98	0.03	0.03		33.73	3.45	3.10	0.81	98.87
970720-5-(1b)-4	36.94	20.86	0.02	0.06		33.61	3.77	3.86	0.21	99.32
970720-5-(1b)-5	36.76	20.86	0.03	0.03		33.37	3.78	3.65	0.26	98.74
970720-5-(2)-1	36.48	20.78	0.07	0.01		32.09	3.70	3.58	0.78	97.48
970720-5-(2)-2	36.20	20.75	0.03	0.02		32.27	3.61	3.81	0.91	97.61
970720-5-(2)-3	36.56	20.80	0.02	0.08		32.24	3.75	3.82	0.66	97.92
970720-5-(2)-4	36.65	20.77	0.04	0.00		32.24	3.50	4.07	0.69	97.96

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Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Total
	%	%	%	%	%	%	%	%	%	
970720-1-1	36.82	20.89	0.07	0.10		31.92	4.51	2.59	1.49	98.39
970720-1-2	36.99	20.98	0.03	0.09		31.45	4.41	3.08	1.54	98.56
970720-1-3	37.42	21.04	0.02	0.00		31.89	4.71	2.84	1.18	99.09
970720-1-4	37.40	21.49	0.05	0.02		31.96	5.52	2.51	0.74	99.69
970720-1-5	36.89	21.14	0.06	0.07		31.70	5.39	2.75	0.86	98.86
10-6-65.4-(1)-1	36.20	20.69	0.00	0.01		34.65	3.56	2.39	1.11	98.61
10-6-65.4-(1)-2	36.36	20.83	0.02	0.00		35.01	3.45	2.10	1.19	98.96
10-6-65.4-(1)-3	36.49	21.13	0.00	0.02		35.27	3.66	1.59	1.13	99.30
10-6-65.4-(1)-4	36.50	20.94	0.07	0.03		32.41	3.77	3.83	1.20	98.76
10-6-65.4-(1)-5	36.54	21.10	0.02	0.00		32.36	3.84	4.03	1.24	99.11
10-6-65.4-(2)-1	36.06	20.86	0.00	0.00	-	32.76	3.81	2.98	1.05	97.52
10-6-65.4-(2)-2	35.65	20.66	0.00	0.00		32.06	4.05	3.23	1.03	96.67
10-6-65.4-(3)-1	36.17	20.48	0.00	0.00		34.49	3.06	2.04	1.89	98.13
10-6-65.4-(3)-2	36.03	20.77	0.00	0.00		34.74	2.99	1.86	1.88	98.27
10-6-65.4-(3)-3	36.26	20.84	0.01	0.00		33.73	3.55	2.83	1.64	98.86
10-6-65,4-(3)-4	36.18	21.06	0.00	0.00		32.54	3.47	3.71	1.52	98.47
10-6-65.4-(3)-5	36.30	20.81	0.04	0.02		31.96	2.69	3.83	3.12	98.77
10-6-65.4-(3)-6	35.91	20.67	0.07	0.01		32.03	2.80	3.95	3.09	98.53
440NQ34-4.3-1	36.93	21.11	0.02	0.00	0.00	26.98	3.91	2.38	7.96	99.29
440NQ34-4.3-2	36.98	21.27	0.00	0.02	0.00	27.65	3.83	3.11	6.53	<b>99.38</b>
440NQ34-4.3-3	37.06	21.09	0.11	0.00	0.00	27.39	3.68	4.28	6.18	99.79
440NQ34-4.3-4	36.89	21.11	0.04	0.00	0.05	27.32	3.56	4.43	5.95	99.34
440NQ34-4.3-5	37.03	21.11	0.10	0.04	0.00	26.98	3.38	4.69	6.14	99.46
440NQ34-4.3-6	36.83	21.06	0.13	0.00	0.09	26.87	3.37	4.49	6.20	99.04
440NQ34-4.3-7	36.71	21.09	0.09	0.00	0.00	27.03	3.47	4.49	6.24	99.11
440NQ34-4.3-8	36.89	21.09	0.06	0.01	0.02	26.77	3.65	4.37	6.14	99.00
440NQ34-4.3-9	37.02	21.17	0.06	0.00	0.00	27.00	3.63	4.53	6.05	99.46
440NQ34-4.3-10	37.03	21.09	0.08	0.00	0.00	27.02	3.64	4.05	6.24	99.13
440NQ34-4.3-11	36.98	21.42	0.02	0.00	0.02	27.17	3.99	2.4 <del>9</del>	7.78	99.87
440NQ34-4.3-(2)-1	36.91	21.22	0.02	0.03	0.00	25.88	3.93	3.49	8.00	99.48

Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	$V_2O_3$	FeO	MgO	CaO	MnO	Totai
•	%	%	%	%	%	%	%	%	%	
440NQ34-4.3-(2)-2	36.93	21.22	0.06	0.03	0.00	26.05	3.79	3.56	7.68	99.32
440NQ34-4.3-(2)-3	36.97	21.14	0.04	0.00	0.00	26.50	3.66	3.50	7.69	99.49
440NQ34-4.3-(2)-4	36,90	21.19	0.02	0.00	0.00	26.35	3.78	3.34	7.80	99.38
440NQ34-4.3-(2)-5	37.00	21.29	0.00	0.02	0.00	26.12	3.96	3.53	7.81	99.74
440NQ34-4.3-(2)-6	36.84	21.26	0.04	0.07	0.02	26.26	3.80	3.64	7.23	99.15
T226-182.5-(1a)-1	37.01	21.27	0.00	0.00	0.00	32.38	5.38	2.26	1.47	99.77
T226-182.5-(1a)-2	37.03	21.16	0.09	0.11	0.02	28.50	4.17	3.70	4.55	99.33
T226-182.5-(1a)-3	37.16	21.21	0.04	0.12	0.04	29.11	4.23	3.40	4.37	99.67
T226-182.5-(1a)-4	37.10	21.28	0.02	0.10	0.00	30.25	4.79	2.98	3.10	99.61
T226-182.5-(1a)-5	37.26	21.45	0.01	0.05	0.04	31.49	5.29	2.47	1.91	99.95
T226-182.5-(1a)-6	37.37	21.62	0.02	0.04	0.01	31.57	5.48	2.36	1.46	<b>99</b> .92
T226-182.5-(1a)-7	37.54	21.48	0.05	0.07	0.06	31.49	5.65	2.35	1.06	<b>99</b> .75
T226-182.5-(1a)-8	37.45	21.56	0.03	0.01	0.04	32.01	4.93	2.24	1.75	100.00
T226-182.5-(1b)-1	37.15	21.44	0.04	0.00	0.01	32.06	4.79	2.44	1.70	99.63
T226-182.5-(1b)-2	37.21	21.39	0.03	0.03	0.00	31.63	5.02	2.55	1.82	<b>99</b> .67
T226-182.5-(1b)-3	37.09	21.28	0.04	0.15	0.02	28.92	4.12	3.40	4.70	99.70
T226-182.5-(1b)-4	37.13	21.10	0.06	0.07	0.03	29.99	4.19	3.33	3.49	99.39
T226-182.5-(2a)-1	37.23	21.47	0.04	0.00	0.01	31.99	4.99	2.43	1.76	99.92
T226-182.5-(2a)-2	37.19	21.30	0.04	0.06	0.02	32.02	5.11	2.26	1.50	99.49
T226-182.5-(2a)-3	37.05	21.24	0.04	0.01	0.04	31.95	4.82	2.37	1.91	99.43
T226-182.5-(2a)-4	36.86	21.35	0.05	0.02	0.01	31.53	4.77	2.53	2.06	99.16
T226-182.5-(2a)-5	36.99	21.33	0.06	0.00	0.00	30.27	4.85	3.15	2.74	99.39
T226-182.5-(2a)-6	37.20	21.17	0.09	0.11	0.06	30.09	4.88	3.12	2.84	99.57
T226-182.5-(2b)-1	36.90	21.21	0.01	0.06	0.06	32.56	4.06	2.14	2,50	<b>99</b> .50
T226-182.5-(2b)-2	36.76	21.30	0.06	0.01	0.02	32.33	4.30	2.21	2.42	99.40
T226-182.5-(2b)-3	37.03	21.31	0.02	0.09	0.00	32.34	4.31	2.22	2.39	<b>99</b> .71
T226-182.5-(2b)-4	36.96	21.28	0.05	0.08	0.01	32.17	5.01	2.18	1.81	99.55
T226-182.5-(2b)-5	36.95	21.57	0.02	0.00	0.02	32.03	5.02	2.28	1.92	99.81

Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Total
	%	%	%	%	%	%	%	%	%	
970720-4-(1)-1	36.68	21.00	0.00	0.02	0.00	31.99	2.77	3.61	3.09	99.17
970720-4-(1)-2	36.75	20.95	0.00	0.01	0.00	32.01	2.69	3.72	2.94	<del>99</del> .07
970720-4-(1)-3	36.82	20.95	0.04	0.03	0.04	28.54	1.70	5.46	5.96	99.53
970720-4-(1)-4	36.71	20.98	0.06	0.00	0.00	29.48	1.87	5.39	4.77	99.24
970720-4-(1)-5	36.62	20.90	0.04	0.01	0.00	31.89	2.44	2.43	4.59	98.91
970720-4-(2)-1	36.45	20.82	0.00	0.02	0.01	31.83	2.31	2.58	4.89	98.89
970720-4-(2)-2	36.32	20.90	0.01	0.03	0.00	31.99	2.25	2.25	5.08	98.84
970720-4-(2)-3	36.41	20.82	0.02	0.04	0.03	31.67	2.85	2.39	4.70	98.93
970720-4-(2)-4	36.68	20.89	0.04	0.00	0.05	31.39	2.70	2.56	4.68	98.97
970720-4-(2)-5	36.49	21.04	0.02	0.00	0.01	32.45	2.71	2.07	4.48	99.26
970720-4-(2)-6	36.45	21.04	0.03	0.01	0.00	32.13	2.66	3.21	3.67	99.20
970720-4-(2)-7	36.75	20.97	0.03	0.03	0.00	31.62	2.53	3.16	4.25	99.33
970720-4-(2)-8	36.54	20.73	0.04	0.09	0.03	30.85	2.51	2.98	5.72	99.49
970720-4-(2)-9	36.40	20.78	0.06	0.02	0.04	30.23	2.32	3.26	5.92	99.02
NGS551-1198.7-(1a)-1	36.96	21.28	0.03	0.06	0.01	34.04	4.05	2.96	0.32	99.71
NGS551-1198.7-(1a)-2	36.71	21.16	0.00	0.07	0.01	33.56	4.35	2.57	0.42	98.85
NGS551-1198.7-(1a)-3	36.84	21.15	0.05	0.07	0.00	33.30	3.99	3.27	0.63	99.29
NGS551-1198.7-(1a)-4	36.83	21.08	0.06	0.08	0.00	33.58	4.17	3.21	0.53	99.54
NGS551-1198.7-(1a)-5	36.85	21.28	0.00	0.01	0.00	34.95	4.27	1.79	0.39	99.53
NGS551-1198.7-(1a)-6	36.98	21.16	0.00	0.01	0.00	33.97	3.90	2.94	0.29	99.26
NGS551-1198.7-(1a)-7	36.82	21.20	0.00	0.05	0.02	35.23	3.83	2.01	0.37	99.53
NGS551-1198.7-(1b)-1	36.91	21.11	0.02	0.00	0.02	34.97	4.10	1.81	0.32	99.25
NGS551-1198.7-(1b)-2	36.98	21.12	0.05	0.08	0.00	32.88	4.07	3.39	0.52	99.08
NGS551-1198.7-(1b)-3	36.85	21.18	0.00	0.01	0.01	34.53	4.11	2.28	0.27	99.24
NGS551-1198.7-(1b)-4	36.89	21.06	0.02	0.06	0.00	34.40	4.13	2.29	0.26	99.11
NGS551-1198.7-(1b)-5	36.97	21.11	0.03	0.07	0.03	33.69	3.45	2.37	1.91	99.64
NGS551-1198.7-(1b)-6	36.78	21.06	0.01	0.08	0.01	33.92	3.63	2.20	1.82	99.52
NGS551-1198.7-(2a)-1	36.72	21.06	0.01	0.03	0.03	34.60	4.24	1.88	0.32	98.89
NGS551-1198.7-(2a)-2	36.90	21.28	0.00	0.04	0.00	34.37	4.47	1.98	0.31	99.35
NGS551-1198.7-(2a)-3	36.96	21.11	0.04	0.05	0.01	33.46	4.23	3.12	0.35	99.33
NGS551-1198.7-(2a)-4	36.89	21.16	0.00	0.09	0.04	34.82	3.91	1.92	0.39	99.21

Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Total
	%	%	%	%	%	%	%	%	%	
NGS551-1198.7-(2a)-5	36.92	21.07	0.00	0.08	0.01	34.71	4.06	1.92	0.38	99.16
NGS551-1198.7-(2a)-6	36.96	21.02	0.00	0.12	0.00	34.06	4.07	2.12	1.12	99.48
NGS551-1198.7-(2a)-7	36.58	20.94	0.01	0.01	0.00	33.83	4.07	2.11	1.05	98.59
NGS551-1198.7-(2a)-8	36.68	21.03	0.02	0.08	0.05	34.10	4.11	2.02	1.05	99.12
8-44-231.4-1	36.69	20.69	0.04	0.03	0.05	33.63	3.03	3.04	1.85	99.03
8-44-231.4-2	36.81	20.92	0.06	0.00	0.07	34.28	3.72	1.94	1.65	99.45
8-44-231.4-3	36.50	20.47	0.07	0.01	0.12	34.39	3.70	1.77	1.74	98.78
8-44-231.4-4	36.75	20.79	0.00	0.00	0.00	34.28	3.85	1.67	1.59	98.92
8-44-231.4-5	36.17	20.50	0.03	0.00	0.03	32.62	4.43	1.49	1.59	96.87
8-44-231.4-6	36.48	20.84	0.00	0.04	0.06	35.04	3.36	1.58	1.71	99.10
8-44-231.4-7	36.52	20.86	0.02	0.04	0.00	33.89	3.62	2.50	1.66	99.10
8-44-231.4-8	36.65	20.85	0.01	0.00	0.03	34.64	2.89	2.09	1.98	99.13
8-44-231.4-9	36.69	20.84	0.01	0.00	0.05	34.27	2.85	2.93	1.75	99.41
8-44-231.4-10	36.79	20.90	0.06	0.00	0.02	33.72	2.93	4.00	0.99	99.40
8-44-231.4-11	36.58	20.95	0.03	0.00	0.01	33.96	2.7 <del>9</del>	3.94	1.11	99.38
8-44-231.4-12	36.70	20.83	0.05	0.01	0.00	33.91	2.55	4.13	1.41	99.59
8-44-231.4-13	36.58	20.71	0.00	0.00	0.03	33.67	2.45	3.83	1.59	98.84
8-44-231.4-14	36.54	20.61	0.04	0.00	0.01	33.58	2.34	4.14	1.68	98.93
8-44-231.4-15	36.69	20.80	0.06	0.00	0.02	33.35	2.64	3.78	1.60	98.93
8-44-231.4-16	36.70	20.90	0.08	0.06	0.03	33.20	2.93	3.90	1.48	99.27
8-44-231.4-17	36.58	20.85	0.04	0.00	0.00	33.23	2.82	3.83	1.60	98.95
8-44-231.4-18	36.18	20.57	0.02	0.00	0.05	35.01	2.25	2.33	2.48	98.88
8-44-231.4-19	36.81	20.81	0.00	0.02	0.00	34.23	3.52	2.31	1.56	99.26
8-44-231.4-20	37.19	20.57	0.01	0.05	0.02	34.72	3.69	1.59	1.60	99.44
8-44-231.4-21	36.74	20.80	0.01	0.02	0.00	34.96	3.57	1.88	1.56	99.54
8-44-231.4-22	36.95	20.92	0.06	0.00	0.03	33.48	3.28	3.74	1.27	99.72
8-44-231.4-23	36.68	20.96	0.02	0.00	0.02	34.07	2.73	3.50	1.84	99.83
8-44-231.4-24	36.64	20.89	0.01	0.00	0.01	33.39	3.05	3.47	1.67	99.13
8-44-231.4-25	36.90	20.94	0.14	0.03	0.03	33.37	2.80	3.63	1.88	99.71
8-44-231.4-26	36.48	20.78	0.06	0.02	0.04	33.11	2.40	4.23	2.46	<b>99.59</b>
8-44-231.4-27	36.51	20.76	0.00	0.04	0.00	33.54	2.43	3.09	2.75	99.11
8-44-231.4-28	36.43	20.78	0.00	0.00	0.06	33.84	2.48	2.92	2.74	<del>99</del> .25

Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>		V <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Total
	%	%	%	%	%	%	%	%	%	
8-44-231.4-29	36.49	20.80	0.06	0.00	0.01	34.13	2.34	3.17	2.57	99.57
8-44-231.4-30	36.81	20.79	0.00	0.00	0.00	33.50	2.81	3.71	1.98	99.59
8-44-231.4-31	36.45	20.94	0.03	0.01	0.02	33.64	2.85	3.44	1.89	99.26
8-44-231.4-32	36.54	21.02	0.02	0.00	0.04	34.58	2.68	2.56	2.09	99.54
8-44-231.4-33	36.74	20.77	0.03	0.02	0.00	33.35	3.09	3.30	1.7 <b>2</b>	99.01
8-44-231.4-34	36.39	20.75	0.01	0.00	0.03	34.04	3.15	2.43	2.10	98.89
8-44-231.4-35	36.40	20.90	0.02	0.00	0.03	34.06	3.35	1.88	2.19	98.82
8-44-231.4-36	36.34	20.65	0.01	0.01	0.01	34.14	3.19	2.06	2.31	98.71
8-44-231.4-37	36.82	20.73	0.01	0.00	0.04	34.07	3.38	1.85	2.34	99.24
8-44-231.4-38	36.48	20.68	0.00	0.02	0.00	33.99	3.31	1.90	2.40	98.78
T226-135.3-1	36.50	20.93	0.01	0.02	0.00	30.31	2.95	2.37	6.51	99.59
T226-135.3-2	36.55	20.73	0.02	0.00	0.06	30.39	3.34	2.44	5.44	98.96
T226-135.3-3	36.64	20.88	0.03	0.04	0.00	30.49	3.18	3.18	5.04	99.49
T226-135.3-4	36.58	20.71	0.31	0.02	0.08	30.34	3.12	3.32	4.99	99.47
T226-135.3-5	36.52	20.92	0.05	0.00	0.01	30.38	3.14	3.14	5.10	99.26
T226-135.3-6	36.46	20.70	0.37	0.05	0.00	30.26	3.10	3.08	5.27	99.27
T226-135.3-7	36.43	20.76	0.03	0.00	0.01	30.48	3.03	2.39	6.21	99.33
T226-135.3-8	36.34	20.68	0.01	0.02	0.04	30.06	2.78	2.41	6.70	99.02
T221-42.5-1	36.51	20.81	0.06	0.02	0.00	33.00	2.57	1.96	4.72	99.65
T221-42.5-2	34.19	19.71	3.62	0.02	0.02	31.44	3.74	1.51	4.16	98.42
T221-42.5-3	36.44	20.87	0.40	0.00	0.04	32.57	2.83	2.16	4.57	99.87
T221-42.5-4	36.68	20.96	0.01	0.02	0.00	32.76	2.78	2.13	4.67	100.00
T221-42.5-5	36.57	20.95	0.02	0.01	0.00	32.44	2.84	2.13	4.80	<b>9</b> 9.77
T221-42.5-6	36.66	20.80	0.03	0.00	0.00	32.22	2.74	2.22	4.64	99.32
T221-42.5-7	36.60	20.66	0.09	0.00	0.00	32.47	2.72	2.13	4.54	99.20
T221-42.5-8	36.50	20.82	0.00	0.08	0.03	32.82	2.66	2.05	4.73	99.69
T221-42.5-9	36.44	21.02	0.01	0.00	0.05	33.21	2.53	1.72	4.65	99.62
T221-42.5-10	36.55	20.81	0.10	0.01	0.03	32.91	2.95	2.28	3.92	99.55

Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Total
	%	%	%	%	%	%	%	%	%	
T221-42.5-11	36.61	20.81	0.02	0.01	0.00	32.36	2.70	2.09	4.65	99.24
T221-42.5-12	36.28	20.72	0.02	0.04	0.03	32.06	2.56	2.22	5.21	99.14
T221-42.5-13	36.50	20.75	0.04	0.06	0.00	31.97	2.46	2.08	5.77	99.63
T221-42.5-14	36.46	20.82	0.05	0.02	0.01	31.58	2.36	2.07	6.00	99.37
T221-42.5-15	36.27	20.80	0.08	0.02	0.00	31.64	2.48	2.03	5.95	99.26
T221-42.5-16	36.51	20.74	0.06	0.06	0.01	31.96	2.61	1.75	5.71	99.40
T221-42.5-17	36.49	20.72	0.00	0.04	0.05	32.05	2.58	1.89	5.51	99.33
T221-42.5-18	36.76	20.87	0.05	0.02	0.00	32.28	2.59	2.12	5.00	99.68
970705-3-1	36.48	20.96	0.06	0.02	0.00	29.77	2.88	3.45	5.26	98.88
970705-3-2	36.58	20.86	0.05	0.05	0.02	29.48	2.97	3.65	5.26	98.90
970705-3-3	36.49	20.86	0.04	0.02	0.06	29.29	3.08	3.79	5.23	98.86
970705-3-4	36.68	20.85	0.00	0.00	0.00	29.30	3.02	3.85	5.36	99.07
970705-3-5	36.52	20.88	0.09	0.03	0.02	<b>29</b> .17	2.97	3.96	5.15	98.77
970705-3-6	36.62	20.97	0.10	0.05	0.00	29.99	3.08	3.14	5.24	<b>99.19</b>
970705-3-7	36.52	21.04	0.08	0.01	0.00	30.02	3.11	3.22	5.15	<b>99</b> .15
970705-3-8	36.17	20.71	0.00	0.00	0.01	30.60	2.78	2.83	5.49	98.58
970705-3-10	36.54	20.94	0.06	0.01	0.02	30.26	3.07	3.26	4.99	99.16
970705-3-11	36.28	20.86	0.00	0.00	0.04	30.11	3.01	3.39	4.96	98.66
970705-3-12	36.52	20.83	0.07	0.06	0.06	30.16	3.04	3.29	5.16	99.18
970705-3-13	36.28	20.78	0.06	0.01	0.06	30.05	2.94	3.19	5.30	98.68
970705-3-14	36.52	20.84	0.03	0.00	0.00	30.00	2.90	3.48	5.16	98.93
970705-3-15	36.71	20.83	0.03	0.02	0.00	30.15	2.83	3.20	5.33	99.09
970705-3-16	36.15	20.81	0.03	0.03	0.03	30.40	2.92	2.71	5.45	98.53
970705-3-17	36.18	20.68	0.02	0.03	0.00	30.24	2.85	2.87	5.46	98.33
970705-3-18	36.49	20.79	0.04	0.05	0.04	30.08	2.99	3.21	5.21	98.89
970705-3-20	36.23	20.75	0.06	0.01	0.01	29.82	3.00	3.41	5.01	98.29
970705-3-21	36.27	20.73	0.08	0.00	0.05	29.62	2.96	3.57	4.96	98.25
970705-3-22	36.64	20.87	0.00	0.00	0.00	30.47	3.07	2.74	5.11	98.91
970705-3-23	35.92	20.54	0.08	0.00	0.04	29.77	2.71	3.19	5.36	97.61
970705-3-25	36.45	20.77	0.00	0.04	0.05	30.43	3.14	2.74	5.30	98.91
970705-3-26	36.48	20.75	0.02	0.03	0.00	30.37	3.17	2.76	5.09	98.66
970705-3-27	36.24	20.82	0.00	0.06	0.03	30.36	3.09	2.62	5.19	98.40
970705-3-28	36.60	20.89	0.03	0.04	0.01	29.92	3.08	3.15	5.12	98.84
970705-3-29	36.33	20.92	0.01	0.05	0.00	30.24	2.87	2.71	5.52	98.65

Metapelite gamet 8

## Hemio Garnet Traverse Probe Data

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 20 nA; 20 s peak counts; 5 um beam. Total Fe as FeO. Lower detection limits at 2SD are 0.01-0.02 wt %. Orthoclase-, albite, spessartine, garnet, TiO2 and diopside-based standards for all major elements.

Sample	Comment	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub> %	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Total
8-44-231.4-1	rim	26.00			70	70	%	%	%	%	%
8-44-231.4-2	*****	30.09	20.69	0.04	0.03	0.05	33.63	3.03	3.04	1.85	99.03
8-44-231 4-3		30.81	20.92	0.06	0.00	0.07	34.28	3.72	1.94	1.65	99.45
8-44-231 4-4	0070	35.50	20.47	0.07	0.01	0.12	34.39	3.70	1.77	1.74	98.78
8.44.221 4 5	COLO	36,75	20.79	0.00	0.00	0.00	34.28	3.85	1.67	1.59	98.92
8-14-201.4-0		36.17	20.50	0.03	0.00	0.03	32.62	4.43	1.49	1.59	96.87
8-44 221 4 7		36.48	20.84	0.00	0.04	0.06	35.04	3.36	1.58	1.71	99.10
8 44 221 4 9	at	36.52	20.86	0.02	0.04	0.00	33.89	3.62	2.50	1.66	99 10
0-44-231.4-0	nm	36.65	20.85	0.01	0.00	0.03	34.64	2.89	2.09	1.98	99.13
8-44-231.4-9	літ	36.69	20.84	0.01	0.00	0.05	34 27	2 95	2.02	4 75	<b>.</b>
8-44-231.4-10		36.79	20.90	0.06	0.00	0.00	22 70	2.00	2.90	1./5	99.41
8-44-231.4-11		36.58	20.95	0.03	0.00	0.02	33.06	2.80	4.00	0.99	99.40
8-44-231.4-12		36.70	20.83	0.05	0.00	0.01	33.01	2.19	3.94	1.11	99.38
8-44-231.4-13		36.58	20.71	0.00	0.01	0.00	22.81	2.00	4.13	1.41	99.59
8-44-231.4-14	center	36.54	20.61	0.00	0.00	0.03	33.07	2.45	3.83	1.59	98.84
8-44-231.4-15		36.69	20.80	0.04	0.00	0.01	33.38	2.34	4.14	1.68	98.93
8-44-231.4-16		36 70	20.00	0.00	0.00	0.02	33.35	2.64	3.78	1.60	98.93
8-44-231.4-17		36.58	20.90	0.00	0.00	0.03	33.20	2.93	3.90	1.48	99.27
8-44-231.4-18	rim	30.30	20.00	0.04	0.00	0.00	33.23	2.82	3.83	1.60	98.95
		30.10	20.37	0.02	0.00	0.05	35.01	2.25	2.33	2.48	98.88
8-44-231.4-19	rim	36.81	20.81	0.00	0.02	0.00	24.00	2.50	0.04		
8-44-231.4-20		37 19	20.57	0.00	0.02	0.00	34.23	3.52	2.31	1.56	99.26
8-44-321.4-21	core	36 74	20.07	0.01	0.05	0.02	34.72	3.69	1.59	1.60	99.44
8-44-231.4-22	-	36 95	20.00	0.01	0.02	0.00	34.96	3.57	1.88	1.56	99.54
8-44-231.4-23	rim	36.69	20.92	0.00	0.00	0.03	33.48	3.28	3.74	1.27	99.72
		00.00	20.90	0.02	0.00	0.02	34.07	2.73	3.50	1.84	<del>9</del> 9.83

#### Weight %

Garnet traverse 1

Sample	Comment	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO₂	Cr <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Total
		%	%	%	%	%	%	%	%0	%	%
8-44-231.4-24	rim	36.64	20.89	0.01	0.00	0.01	33.39	3.05	3.47	1.67	<del>9</del> 9.13
8-44-231.4-25	(repeat analysis rim)	36.90	20,94	0.14	0.03	0.03	33.37	2.80	3.63	1.88	99.71
8-44-231.4-26		36.48	20.78	0.06	0.02	0.04	33.11	2.40	4.23	2.46	<del>9</del> 9.59
8-44-231.4-27		36.51	20.76	0.00	0.04	0.00	33.54	2.43	3.09	2.75	<b>99.11</b>
8-44-231.4-28		36.43	20.78	0.00	0.00	0.06	33.84	2.48	2.92	2.74	99.25
8-44-231.4-29		36.49	20.80	0.06	0.00	0.01	34.13	2.34	3.17	2.57	99.57
8-44-231.4-30		36.81	20.79	0.00	0.00	0.00	33.50	2.81	3.71	1.98	99.59
8-44-231.4-31	rim (in line of traverse)	36.45	20.94	0.03	0.01	0.02	33.64	2.85	3.44	1.89	99.26
8-44-231.4-32	rim (not on traverse line)	36.54	21.02	0.02	0.00	0.04	34.58	2.68	2.56	2.09	99.54
8-44-231.4-33	rim	36.74	20.77	0.03	0.02	0.00	33.35	3.09	3.30	1.72	99.01
8-44-231.4-34		36.39	20.75	0.01	0.00	0.03	34.04	3.15	2.43	2.10	98.89
8-44-231.4-35		36.40	20.90	0.02	0.00	0.03	34.06	3.35	1.88	2.19	98.82
8-44-231.4-36		36.34	20.65	0.01	0.01	0.01	34.14	3.19	2,06	2.31	98.71
8-44-231.4-37		36.82	20.73	0.01	0.00	0.04	34.07	3.38	1.85	2.34	99.24
8-44-231.4-38	core	36.48	20.68	0.00	0.02	0.00	33.99	3.31	1.90	2.40	98.78
T226-135.3-1	rim	36.50	20.93	0.01	0.02	0.00	30.31	2.95	2.37	6.51	99.59
T226-135.3-2		36.55	20.73	0.02	0.00	0.06	30.39	3.34	2.44	5.44	98.96
T226-135.3-3		36.64	20.88	0.03	0.04	0.00	30.49	3.18	3.18	5.04	99.49
T226-135.3-4		36.58	20.71	0.31	0.02	0.08	30.34	3.12	3.32	4.99	99.47
T226-135.3-5	core	36.52	20.92	0.05	0.00	0.01	30.38	3.14	3.14	5.10	99.26
T226-135.3-6		36.46	20.70	0.37	0.05	0.00	30.26	3.10	3.08	5.27	99.27
T226-135.3-7		36.43	20.76	0.03	0.00	0.01	30.48	3.03	2.39	6.21	99.33
T226-135.3-8	rim	36.34	20.68	0.01	0.02	0.04	30,06	2.78	2.41	6.70	99.02
T221-42.5-1	rim	36.51	20.81	0.06	0.02	0.00	33.00	2.57	1.96	4.72	99.65
T221-42.5-2		34.19	19.71	3.62	0.02	0.02	31.44	3.74	1.51	4.16	98.42
T221-42.5-3		36.44	20.87	0.40	0.00	0.04	32.57	2.83	2.16	4.57	99.87
T221-42.5-4		36.68	20.96	0.01	0.02	0.00	32.76	2.78	2.13	4.67	100.00
T221-42.5-5	core	36.57	20.95	0.02	0.01	0.00	32.44	2.84	2.13	4.80	99.77
T221-42.5-6		36.66	20.80	0.03	0.00	0.00	32.22	2.74	2.22	4.64	99.32
T221-42.5-7		36.60	20.66	0.09	0.00	0.00	32.47	2.72	2.13	4.54	99.20
T221-42.5-8	rim	36.50	20.82	0.00	0.08	0.03	32.82	2.66	2.05	4.73	99.69

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Sample	Comment	SiOz	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Total
		%	%	%	%	%	%	%	%	%	%
T221-42.5-9	nim	36.44	21.02	0.01	0.00	0.05	33.21	2.53	1.72	4.65	99.62
T221-42.5-10		36.55	20.81	0.10	0.01	0.03	32.91	2.95	2.28	3.92	99.55
T221-42.5-11		36.61	20.81	0.02	0.01	0.00	32.36	2.70	2.0 <del>9</del>	4.65	99.24
T221-42.5-12		36.28	20.72	0.02	0.04	0.03	32.06	2.56	2.22	5.21	99.14
T221-42.5-13	core	36.50	20.75	0.04	0.06	0.00	31.97	2.46	2.08	5.77	99.63
T221-42.5-14	core	36.46	20.82	0.05	0.02	0.01	31.58	2.36	2.07	6.00	99.37
T221-42.5-15		36.27	20.80	0.08	0.02	0.00	31.64	2.48	2.03	5.95	99.26
T221-42.5-16		36.51	20.74	0.06	0.06	0.01	31.96	2.61	1.75	5.71	99.40
T221-42.5-17		36.49	20.72	0.00	0.04	0.05	32.05	2.58	1.89	5.51	99.33
T221-42.5-18	rim	36.76	20.87	0.05	0.02	0.00	32.28	2.59	2.12	5.00	99.68
970705-3-1	rim	36.48	<b>20.96</b>	0.06	0.02	0.00	29.77	2.88	3.45	5.26	98.88
970705-3-2		36.58	20.86	0.05	0.05	0.02	29.48	2.97	3.65	5.26	98.90
970705-3-3		36.49	20.86	0.04	0.02	0.06	29.29	3.08	3.7 <del>9</del>	5.23	98.86
970705-3-4	core	36.68	20.85	0.00	0.00	0.00	29.30	3.02	3.85	5.36	99.07
970705-3-5	core	36.52	20.88	0.09	0.03	0.02	<b>29</b> .17	2.97	3.96	5.15	98.77
970705-3-6		36.62	20.97	0.10	0.05	0.00	29.99	3.08	3.14	5.24	99.19
970705-3-7		36.52	21.04	0.08	0.01	0.00	30.02	3.11	3.22	5.15	99.15
970705-3-8	rim	36.17	20.71	0.00	0.00	0.01	30.60	2.78	2.83	5.49	98.58
970705-3-10	rim	36.54	20. <del>9</del> 4	0.06	0.01	0.02	30.26	3.07	3.26	4.99	99.16
970705-3-11	core	36.28	20.86	0.00	0.00	0.04	30.11	3.01	3.39	4.96	98.66
970705-3-12	core	36.52	20.83	0.07	0.06	0.06	30.16	3.04	3.29	5.16	<del>99</del> .18
970705-3-13		36.28	20.78	0.06	0.01	0.06	30.05	2.94	3.19	5.30	98.68
970705-3-14		36.52	20.84	0.03	0.00	0.00	30.00	2.90	3.48	5.16	98.93
970705-3-15	rim	36.71	20.83	0.03	0.02	0.00	30.15	2.83	3.20	5.33	99.09
970705-3-16	rim (not on traverse line)	36.15	20.81	0.03	0.03	0.03	30.40	2.92	2.71	5.45	<del>9</del> 8.53
970705-3-17	rim	36.18	20.68	0.02	0.03	0.00	30.24	2.85	2.87	5.46	98.33
970705-3-18		36.49	20.79	0.04	0.05	0.04	30.08	2.99	3.21	5.21	98.89
970705-3-19		35.94	20.67	0.14	0.03	0.00	29.51	3.10	3.05	5.01	97.45
970705-3-20		36.23	20.75	0.06	0.01	0.01	29.82	3.00	3.41	5.01	98.29
970705-3-21		36.27	20.73	0.08	0.00	0.05	29.62	2.96	3.57	4.96	98.25
970705-3-22		36.64	20.87	0.00	0.00	0.00	30.47	3.07	2.74	5.11	98.91
970705-3-23	rim	35. <del>9</del> 2	20.54	0.08	0.00	0.04	29.77	2.71	3.19	5.36	97.61

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Garnet traverse 3

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Sample		Comment	SiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	TiO₂ %	Cr <sub>2</sub> O <sub>3</sub> %	V <sub>2</sub> O <sub>3</sub> %	FeO %	MgO %	CaO %	MnO %	Total %
970705-3-24	rim		35.55	20.42	0.07	0.04	0.00	29.69	2.76	3.38	5.34	97.24
970705-3-25			36.45	20.77	0.00	0.04	0.05	30.43	3.14	2.74	5.30	98.91
970705-3-26	core		36.48	20.75	0.02	0.03	0.00	30.37	3.17	2.76	5.09	98.66
970705-3-27	core		36.24	20.82	0.00	0.06	0.03	30.36	3.09	2.62	5.19	98.40
970705-3-28			36.60	20.89	0.03	0.04	0.01	29.92	3.08	3.15	5.12	98.84
970705-3-29	rim		36.33	20.92	0.01	0.05	0.00	30.24	2.87	2.71	5.52	98.65

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Garnet traverse 4

### Hemlo Mica Probe Data

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 20 nA; 20 s peak counts; 5 um beam.

Total Fe as FeO. Lower detection limits at 2SD are 0.01-0.02 wt %.

Orthoclase-, albite, spessartine, garnet, and diopside-based standards for all major elements.

Note that biotite in the vicinity of the deposit is frequently chloritized and therefore unsuitable for geothermobarometry.

Sample	Comment	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO	BaO %	Na <sub>2</sub> O	K₂O %	Total
		70	70	70	70	70	76	70	70	70	70	70	
T226-8-1	chloritized biotite	33.65	1.49	19.25	0.22	21.40	0.02	10.44	0.25	0.05	0.26	7.46	94.57
T226-8-2	biotite	34.59	1.51	19.40	0.17	20.38	0.03	10.71	0.09	0.05	0.16	8.60	95.76
T226-8-3	biotite	35.56	1.59	19.22	0.21	19.41	0.02	10.42	0.00	0.06	0.36	9.54	96.50
T226-8-4	chloritized biotite	33.55	1.27	18.83	0.19	21.02	0.05	10.43	0.00	0.23	0.26	7.96	93.87
T226-8-5	biotite	33.99	1.80	19.53	0.12	19.75	0.04	9.83	0.08	0.15	0.30	8.47	94.18
T226-8-6	chloritized biotite	31.02	1.75	20.09	0.13	23.82	0.05	10.70	0.61	0.00	0.11	4.11	92.48
T226-8-7	biotite	35.31	1.72	19.23	0.11	20.29	0.02	10.13	0.00	0.11	0.31	9.54	96.85
T226-8-8	biotite	34.65	1.72	19.45	0.11	20.86	0.00	9.98	0.09	0.03	0.33	8.66	95.94
T226-175-1	biotite	37.05	1.53	17.54	0.08	15.25	0.14	14.77	0.08	0.32	0.22	8.99	96.15
T226-175-2	biotite	37.45	1.35	18.12	0.11	14.90	0.12	15.06	0.03	0.23	0.54	8.61	96.71
T226-175-3	biotite	37.60	1.40	17.95	0.05	14.63	0.07	14.72	0.00	0.29	0.51	9.11	96.50
T226-175-4	biotite	36.20	1.38	17.10	0.08	14.55	0.09	14.66	0.02	0.25	0.44	8.18	93.19
T226-175-5	chloritized biotite	33.63	1.03	18.01	0.07	16.67	0.10	17.05	0.04	0.17	0.06	5.84	92.85
T226-175-6	chloritized biotite	36.10	1.37	17.72	0.11	15.34	0.05	15.78	0.03	0.13	0.37	7.65	94.87
T226-175-(2)-1	biotite	37.31	1.51	17.60	0.09	15.05	0.03	14.86	0.03	0.17	0.35	9.21	96.39
T226-175-(2)-2	biotite	37.36	1.52	17.92	0.08	14.63	0.07	15.08	0.02	0.32	0.32	9.52	96.96
T226-175-(2)-3	biotite	36.30	1.24	18.20	0.07	14.96	0.06	15.66	0.04	0.27	0.20	8.34	95.55
T226-175-(2)-4	biotite	37.60	1.51	18.17	0.07	14.74	0.07	15.04	0.01	0.27	0.43	8.86	96.90
T226-175-(2)-5	biotite	36.87	1.50	18.01	0.11	15.09	0.06	15.11	0.02	0.11	0.20	9.26	96.47
T226-175-(3)-1	chloritized biotite	34.08	0.85	17.88	0.06	17.07	0.09	17.27	0.05	0.05	0.24	5.39	93.17
T226-175-(3)-2	biotite	36.80	1.32	17.92	0.06	15.48	0.11	15.36	0.01	0.23	0.34	8.41	96.19
T226-175-(3)-3	biotite	36.96	1.46	18.19	0.06	14.86	0.05	15.21	0.01	0.09	0.44	8.76	96.24
T226-175-(3)-4	biotite	37.25	1.47	18.00	0.08	14.95	0.07	15.35	0.03	0.19	0.48	8.63	96.67
T226-175-(3)-5	chloritized biotite	36.34	1.42	17.94	0.09	15.08	0.11	15.71	0.10	0.14	0.49	7.63	95.23
T226-175-(3)-6	biotite	36.34	1.50	17.81	0.09	15.11	0.14	15.12	0.05	0.25	0.60	8.22	95.46
T226-175-(3)-7	biotite	37.19	1.55	18.02	0.08	14.90	0.11	15.14	0.08	0.23	0.50	8.53	96.56
T226-175-(3)-8	biotite	36.70	1.54	17.93	0.10	15.04	0.13	15.01	0.04	0.20	0.51	8.57	96.02

Sample	Comment	SiO <sub>2</sub>		Al <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	FeO %	MnO %	MgO %	CaO %	BaO %	Na <sub>2</sub> O %	K₂O %	Total
		~	70		70	70	70	70	~				
970720-5-(1a)-1	chloritized biotite	31.42	1.16	20.76	0.08	19.80	0.03	14.36	0.03	0.06	0.07	5.01	92.88
970720-5-(1a)-2	biotite	36.32	1.72	18.60	0.11	17.82	0.02	11.98	0.06	0.09	0.16	10.16	97.20
970720-5-(1a)-3	biotite	36.38	1.75	18.78	0.09	17.28	0.01	11.77	0.06	0.20	0.16	10.04	96.64
970720-5-(1a)-4	biotite	35.55	1.58	18.10	0.11	17.70	0.05	11.74	0.03	0.15	0.19	10.02	95.33
970720-5-(1a)-5	biotite	35.55	1.74	18.71	0.08	18.12	0.04	11.63	0.00	0.03	0.13	9.69	95. <b>8</b> 4
970720-5-(1a)-6	biotite	36.38	1.79	18.68	0.12	17.04	0.03	11.94	0.01	0.09	0.16	10.32	96.69
970720-5-(1a)-7	biotite	35.41	1.70	17.93	0.10	18.16	0.03	11.50	0.01	0.19	0.09	10.22	95.46
970720-5-(1b)-2	biotite	12.62	1.67	4.26	0.07	17.02	0.01	12.05	0.05	0.18	0.02	10.22	58.25
970720-5-(1b)-3	biotite	34.86	1,69	17.27	0.11	17.83	0.06	0.87	0.08	0.13	0.18	9.90	83.02
970720-5-(1b)-4	biotite	35.15	1.59	18.21	0.10	18.55	0.00	11.88	0.02	0.09	0.09	9.40	95.13
970720-5-(1b)-5	biotite	36.14	1.44	18.48	0.08	17.65	0.06	12.09	0.00	0.22	0.14	10.14	96.56
970720-5-(2)-1	biotite	35.21	1.43	18.03	0.11	17.28	0.04	11.32	0.03	0.17	0.16	9.74	93.59
970720-5-(2)-2	biotite	35.82	1.62	18.52	0.09	17.07	0.03	11.17	0.02	0.15	0.14	9.81	94.60
970720-5-(2)-3	biotite	35.23	1.41	18.21	0.06	16.46	0.04	11.90	0.03	0.18	0.17	9.77	93.61
970720-5-(2)-4	biotite	34.90	1.35	18.64	0.09	17.20	0.06	11.29	0.06	0.11	0.16	9.54	93.52
970720-1-1	biotite	36.64	1.35	17.41	0.13	15.44	0.04	14.52	0.02	0.24	0.06	9. <b>69</b>	95.78
970720-1-2	biotite	36.05	1.31	17.36	0.13	14.89	0.03	14.70	0.02	0.21	0.07	9.55	94.54
970720-1-3	biotite	36.51	1.34	17.49	0.10	14.33	0.03	14.41	0.04	0.27	0.14	9.77	94.65
970720-1-(2)-1	biotite	34.95	1.26	16.90	0.11	14.14	0.03	14.23	0.00	0.20	0.05	9.52	91.65
970720-1-(2)-2	biotite	34.99	1.21	16.68	0.11	14.04	0.00	14.17	0.00	0.28	0.09	9.42	91.25
970720-1-(2)-4	biotite	36.49	1.24	17.38	0.12	13.62	0.03	14.12	0.10	0.17	0.44	8.76	92.71
970720-1-(2)-5	biotite	36.30	1.26	16.58	0.09	14.49	0.04	14.10	0.10	0.24	0.15	8.37	91.99
10-6-65.4-(1)-1	biotite	34.69	1.69	18.75	0.22	16.76	0.03	12.04	0.01	0.30	0.16	9.35	93.99
10-6-65.4-(1)-2	biotite	34.90	1.75	20.23	0.16	15.78	0.03	11.16	0.05	0.39	0.13	9.43	94.02
10-6-65.4-(1)-3	biotite	34.83	2.29	19.07	0.19	17.27	0.06	11.50	0.60	0.36	0.16	8.15	94.51
10-6-65.4-(1)-4	chloritized biotite	31.39	0.84	19.12	0.16	20.95	0.00	14.07	0.04	0.14	0.08	4.38	91.20
10-6-65.4-(1)-5	chlorite	27.31	0.18	19.25	0.15	24.70	0.03	15.36	0.04	0.00	0.00	0.38	87.41
10-6-65.4-(1)-6	chloritized biotite	30.84	1.20	18.89	0.23	21.55	0.05	13.24	0.05	0.14	0.03	4.20	90.49
10-6-65.4-(1)-7	chloritized biotite	34.05	1.68	19.18	0.24	18.12	0.02	12.92	0.05	0.36	0.13	7.28	94.12
10-6-65.4-(1)-8	biotite	35.41	1.89	19.21	0.20	16.86	0.01	12.26	0.02	0.45	0.21	9.06	95.60
10-6-65.4-(1)-9	chlorite	29.12	0.45	19.45	0.22	23.47	0.06	14.92	0.04	0.00	0.02	1.87	89.64
10-6-65.4-(1)-10	chloritized biotite	32.63	0.85	19.72	0.24	20.02	0.02	13.29	0.13	0.03	0.03	4.04	91.02
10-6-65.4-(1)-11	chloritized biotite	34.35	1.46	19.77	0.17	17.20	0.01	12.93	0.00	0.26	0.08	6.76	92.99

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Sample	Comment	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	$V_2O_3$	FeO	MnO	MgO	CaO	BaO	Na <sub>2</sub> O	K <sub>2</sub> O	Total
		%	%	%	%	%	%	%	%	%	%	%	
10-8-65 4-(1)-12	chloritized biotite	34 92	2.07	20 11	0.27	18.00	0.01	11 13	0 12	0.35	0 14	7 44	94.59
10-6-65 4-(1)-12	chloritized biotite	32 43	1 78	19.30	0.18	19.95	0.04	13 14	0.00	0.31	0.05	6.38	93.57
10-6-65 4-(1)-14	chloritized biotite	34 09	1 78	18.87	0.22	17.21	0.04	12.56	0.07	0.15	0.21	7.99	93.27
10-6-65.4-(1)-15	biotite	35 55	2.08	18.80	0.24	15.36	0.05	12.81	0.03	0.42	0.24	9.51	95.11
10-6-65.4-(1)-16	biotite	35.22	2.12	19.27	0.23	16.18	0.03	11.83	0.76	0.30	0.15	8.23	94.30
10-6-65.4-(1)-17	biotite	35.10	1.74	19.21	0.20	17.34	0.02	12.30	0.04	0.23	0.12	8.79	95.08
10-6-65 4-(1)-18	chloritized biotite	32.97	1.45	19.03	0.21	20.01	0.04	12.72	0.03	0.54	0.13	6.71	93.85
10-6-65.4-(1)-19	biotite	34.84	1.87	19.01	0.20	17.56	0.04	12.48	0.01	0.29	0.17	8.37	94.86
970720-4-(1)-1	biotite	35.04	2.13	19.50	0.14	19.90	0.13	8.83	0.01	0.20	0.03	10.57	96.54
970720-4-(1)-2	biotite	35.41	2.12	19.61	0.13	19.55	0.16	8.63	0.01	0.09	0.05	10.64	96.44
970720-4-(1)-3	biotite	35.50	2.08	19.68	0.17	19.90	0.14	8.81	0.02	0.22	0.04	10.58	97.21
970720-4-(1)-4	biotite	35.46	2.01	19.80	0.13	19.40	0.13	8.87	0.04	0.12	0.10	10.53	96.64
970720-4-(1)-5	biotite	35.66	2.06	19.85	0.15	19.56	0.14	8.97	0.04	0.23	0.07	10.55	97.33
970720-4-(1)-6	chlorite	26.49	0.16	21.74	0.06	25.54	0.22	12.75	0.07	0.18	0.05	0.13	87.43
970720-4-(1)-7	chlorite	24.97	0.09	22.78	0.06	25.40	0.23	13.60	0.04	0.03	0.00	0.23	87.48
970720-4-(1)-8	chlorite	24.92	0.04	22.66	0.07	26.26	0.21	13.23	0.05	0.05	0.01	0.02	87.62
970720-4-(2)-1	biotite	34.92	2.04	19.51	0.14	19.90	0.12	8.48	0.06	0.13	0.09	10.29	95.72
970720-4-(2)-2	biotite	34.40	2.16	19.12	0.13	20.31	0.14	8.76	0.07	0.13	0.12	10.09	95.50
970720-4-(2)-3	biotite	35.12	1.67	19.73	0.14	20.12	0,15	8.54	0.01	0.04	0.07	10.61	96.31
970720-4-(2)-4	biotite	34.94	1.87	19.23	0.14	20.00	0.15	9.10	0.02	0.05	0.09	10.41	96.02
970720-4-(2)-5	biotite	35.22	1.87	19.60	0.11	19.74	0.13	8.74	0.01	0.25	0.07	10.46	96.28
NGS51-1198.7-(1)-1	biotite	35.78	1.43	19.66	0.07	16.86	0.00	11.63	0.03	0.31	0.27	9.83	95. <del>9</del> 6
NGS51-1198.7-(1)-2	biotite	36.03	1.37	19.66	0.06	16.95	0.00	11.73	0.00	0.18	0.34	9.61	95.97
NGS51-1198.7-(1)-3	biotite	36.21	1.40	19.88	0.12	16.47	0.00	11.63	0.02	0.21	0.52	9.58	96.10
NGS51-1198.7-(1)-4	biotite	34.42	1.18	19.99	0.08	17.01	0.04	13.30	0.02	0.21	0.23	8.03	94.62
NGS51-1198.7-(1)-5	chloritized biotite	30.85	0.81	20.98	0.08	18.78	0.00	14.90	0.02	0.21	0.09	4.75	91.51
NGS51-1198.7-(1)-6	chloritized biotite	31.69	1.03	20.40	0.04	18.69	0.00	14.02	0.00	0.09	0.15	6.01	92.18
NGS51-1198.7-(1)-7	chloritized biotite	32.50	1.07	20.35	0.04	17.96	0.02	13.36	0.01	0.18	0.19	7.30	93.02
NGS51-1198.7-(1)-8	chloritized biotite	30.74	0.79	19.86	0.09	19.82	0,00	15.16	0.01	0.05	0.05	3.93	90.60
NGS51-1198.7-(1)-9	biotite	35.81	1.33	19.53	0.11	16.74	0.00	11.73	0.00	0.25	0.21	9.61	95.41
NGS51-1198.7-(1)-10	biotite	35.79	1.39	19.98	0.05	16.75	0.03	11.99	0.01	0.41	0.51	9.03	96.04
NGS51-1198.7-(1)-11	biotite	35.88	1.38	19.85	0.07	16.81	0.01	11.65	0.03	0.48	0.40	9.43	96.08
NGS51-1198.7-(1)-12	biotite	35.07	1.42	19.79	0.06	17.25	0.00	11.82	0.01	0.26	0.21	8.91	94.87
NGS51-1198.7-(1)-13	biotite	35.03	1.67	19.62	0.10	17.27	0.00	12.27	0.01	0.20	0.45	8.39	95.07
Sample	Comment	SiO <sub>2</sub>	TIO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	$V_2O_3$	FeO	MnO	MgO	CaO	BaO	Na <sub>2</sub> O	K <sub>2</sub> O	Total
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		%	%	%	%	%	%	%	%	%	%	%	
NGS51-1198.7-(1)-14	chloritized biotite	32.76	1.46	20.09	0.11	18.41	0.00	13.50	0.00	0.24	0.31	6.43	93.35
NGS51-1198.7-(2)-1	biotite	35.92	1.89	19.59	0.12	16.55	0.04	11.63	0.01	0.41	0.53	9.29	96.17
NGS51-1198.7-(2)-2	biotite	37.18	1.85	20.46	0.09	15.43	0.02	10.55	0.01	0.21	0.35	9.80	96.12
NGS51-1198.7-(2)-3	biotite	35.26	1.70	19.49	0.12	16.84	0.03	12.04	0.03	0.29	0.47	8.64	95.03
NGS51-1198.7-(2)-4	biotite	35.68	2.17	19.46	0.09	17.49	0.00	11.25	0.02	0.39	0.46	9.04	96.22
NGS51-1198.7-(2)-5	biotite	36.16	1.69	19.62	0.07	16.94	0.00	11.60	0.00	0.38	0.55	9.29	96.44
NGS51-1198.7-(2)-6	biotite	36,11	1.82	19.61	0.10	16.66	0.00	11.57	0.00	0.33	0.61	9.35	96.27
NGS51-1198.7-(2)-7	biotite	35.64	1.71	19.73	0.07	17.34	0.00	11.69	0.00	0.28	0.35	8.98	95.91
T226-182.5 (7)-(1)-1	biotite	36.92	1.16	18.21	0.09	14.87	0.05	14.40	0.03	0.11	0.38	8.81	95.17
T226-182.5 (7)-(1)-2	biotite	37.80	1.19	18.42	0.10	14.78	0.05	14.47	0.08	0.00	0.63	8.80	96.45
T226-182.5 (7)-(1)-3	biotite	38.01	1.34	18.12	0.09	14.49	0.04	14.21	0.00	0.12	0.38	9.55	96.49
T226-182.5 (7)-(1)-4	biotite	37.52	1.63	17.85	0.11	14.72	0.00	14.12	0.39	0.21	0.29	9.36	96.34
T226-182.5 (7)-(2)-1	biotite	37.22	1.34	18.05	0.11	15.23	0.04	14.33	0.00	0.25	0.38	9.21	96.32
T226-182.5 (7)-(2)-2	biotite	37.61	1.31	18.29	0.06	14.90	0.06	14.34	0.00	0.28	0.44	9.30	96.73
T226-182.5 (7)-(2)-3	biotite	37.41	1.36	17.87	0.08	14.93	0.03	14.19	0.00	0.12	0.31	9.63	<b>96</b> .09
T226-182.5 (7)-(2)-4	chloritized biotite	34.50	1.07	18.04	0.07	16.76	0.03	16.13	0.02	0.12	0.11	6.55	93.54
T226-182.5 (7)-(2)-5	biotite	37.46	1.25	18.10	0.09	14.95	0.08	14.26	0.00	0.23	0.48	9.10	96.13
T226-182.5 (7)-(2)-6	biotite	36.76	1.18	18.01	0.08	15.09	0.07	14.33	0.10	0.16	0.19	9.29	95.37
T226-182.5 (7)-(2)-7	biotite	37.57	1.29	18.18	0.06	14.56	0.03	14.26	0.05	0.23	0.46	8.76	95.59
T226-182.5 (7)-(2)-8	biotite	36.34	1.17	18.22	0.11	15.63	0.04	14.63	0.00	0.17	0.23	8.66	95.33
T226-182.5 (7)-(2)-9	biotite	36.94	1.18	18.07	0.07	14.89	0.03	14.23	0.05	0.18	0.25	9.42	95.47
T226-182.5 (7)-(2)-10	chloritized biotite	34.68	1.28	17.88	0.15	17.00	0.09	15.13	0.04	0.20	0.20	7.33	94.08
T226-182.5 (7)-(2)-11	biotite	36.34	1.19	17.95	0.11	15.61	0.06	14.52	0.04	0.29	0.34	8.61	95.26
T226-182.5 (7)-(2)-12	biotite	37,73	1.30	18.25	0.10	15.62	0.05	14.38	0.00	0.22	0.41	9.13	97.37
T226-182.5 (7)-(2)-13	biotite	37.75	1.30	18.10	0.12	15.42	0.04	14.09	0.01	0.23	0.43	9.14	96.88
T226-182.5 (7)-(2)-14	biotite	37.43	1.25	18.00	0.11	15.13	0.02	14.45	0.07	0.11	0.44	8.77	96.00
T226-182.5 (7)-(2)-15	biotite	36.70	1.21	17.96	0.08	16.02	0.01	14.10	0.00	0.23	0.42	8.56	95.56
T226-182.5 (7)-(2)-16	biotite	36.56	1.31	18.18	0.08	15.84	0.03	14.52	0.03	0.27	0.54	8.01	95.61
T226-182.5 (7)-(2)-17	biotite	36.98	1.27	18.14	0.14	15.44	0.01	14.39	0.01	0.18	0.43	8.40	95.62

Sample	Comment	SiO₂ %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	V₂O₃ %	FeO %	MnO %	MgO %	CaO %	BaO %	Na₂O %	K₂O %	Totai
8-44-231.4-1	chloritized biotite	35.75	0.43	22.25	0.16	17.29	0.10	9.21	0.05	0.02	0.01	4.75	90.00
8-44-231.4-2	chlorite	26.42	0.13	20.04	0.22	27.24	0.09	13.53	0.05	0.01	0.00	0.07	87.78
8-44-231.4-3	chlorite	26.66	0.07	19.81	0.13	26.72	0.07	14.40	0.02	0.02	0.00	0.12	88.01
8-44-231.4-4	biotite	35.80	1.57	19.13	0.12	17.91	0.04	11.02	0.01	0.48	0.19	9.64	95.91
8-44-231.4-5	chlorite	25.32	0.11	22.41	0.16	24.02	0.08	15.62	0.01	0.00	0.00	0.08	87.81
8-44-231.4-6	chlorite	25.22	0.06	22.37	0.06	24.51	0.09	15.34	0.01	0.05	0.02	0.03	87.76
8-44-231.4-7	chlorite	24.96	0.09	23.56	0.23	24.67	0.04	14.62	0.01	0.00	0.00	0.01	88.18
8-44-231.4-8	chlorite	24.93	0.10	23.23	0.16	24.85	0.07	14.81	0.01	0.00	0.01	0.13	88.30
8-44-231.4-9	biotite	34.18	1.41	18.61	0.19	19.03	0.02	11.06	0.05	0.50	0.13	8.27	93.45
8-44-231.4-10	chlorite	29.42	1.36	18.71	0.17	25.25	0.09	11.37	1.11	0.20	0.03	1.92	89.61
8-44-231.4-11	chiorite	27.30	0.30	19.92	0.14	25.58	0.06	13.31	0.30	0.00	0.02	0.49	87.41
8-44-231.4-12	chlorite	28.11	4.76	17.76	0.15	20.47	0.06	12.24	5.49	0.00	0.01	0.09	89.12
8-44-231.4-13	chlorite	28.70	1.35	18.60	0.12	27.20	0.11	10.75	1.21	0.04	0.03	1.36	89.49
8-44-231.4-14	chloritized biotite	33.46	1.18	19.24	0.09	21.50	0.07	9.70	0.02	0.31	0.10	7.60	93.27
8-44-231.4-15	chlorite	24.97	0.08	23.13	0.08	25.33	0.06	14.41	0.00	0.00	0.00	0.09	88.15
8-44-231.4-16	biotite	35.96	1.57	19.24	0.17	18.03	0.01	10.40	0.01	0.54	0.09	10.13	96.15
8-44-231.4-17	chloritized biotite	34.08	1.95	19.00	0.20	18.79	0.04	10.98	0.85	0.39	0.13	7.96	94.38
8-44-231.4-18	chlorite	26.19	0.14	20.55	0.10	27.24	0.08	13.24	0.04	0.04	0.01	0.05	87.68
8-44-231.4-19	chlorite	26.46	0.67	20.52	0.13	26.93	0.11	12.81	0.31	0.00	0.00	0.22	88.16
8-44-231.4-20	biotite	35.94	1.60	19.17	0.15	18.18	0.03	10.94	0.01	0.35	0.16	8.82	95.34
8-44-231.4-21	biotite	35.92	1.48	19.62	0.21	17.26	0.02	10.82	0.00	0.15	0.21	9.98	95.65
8-44-231.4-22	chloritized biotite	34.36	1.26	19.86	0.19	18.53	0.03	11.58	0.04	0.30	0.07	7.17	93.37
8-44-231.4-23	biotite	35.78	1.93	19.03	0.11	17.76	0.04	10.56	0.00	0.65	0.22	10.06	96.14
8-44-231.4-24	biotite	35.35	1.71	19.03	0.11	18.77	0.06	10.47	0.00	0.26	0.14	9.68	95.59
8-44-231.4-25	biotite	35.07	1.53	19.41	0.15	18.65	0.05	10.77	0.08	0.34	0.23	9.11	95.38
8-44-231.4-26	biotite	35.47	1.54	19.08	0.15	17.90	0.05	10.77	0.00	0.15	0.18	10.00	95.29
8-44-231.4-27	chloritized biotite	34.29	1.16	19.99	0.15	19.22	0.07	10.81	0.06	0.46	0.13	7.38	93.71
8-44-231.4-28	chlorite	25.88	0.04	20.40	0.09	28.11	0.13	13.08	0.03	0.05	0.00	0.03	87.83
8-44-231.4-29	biotite	35.65	1.51	19.84	0.15	17.53	0.03	10.46	0.01	0.48	0.19	9,99	95.84
8-44-231.4-30	biotite	35.96	1.75	20.35	0.16	16.78	0.01	9.50	0.02	0.25	0.17	10.01	94.95
8-44-231.4-31	biotite	35.34	1.57	19.66	0.07	17.52	0.04	10.48	0.01	0.43	0.15	9.61	94.88
8-44-231.4-32	biotite	35.52	1.81	19.24	0.11	18.47	0.04	10.35	0.02	0.41	0.20	10.03	96.19

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Sample	Comment	SiO₂ %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	V₂O₃ %	FeO %	MnO %	MgO %	CaO %	BaO %	Na <sub>2</sub> 0 %	K₂O %	Total
T226-135 3-1	muscovite	46 38	0.61	34.76	0.04	0.76	0.03	0.64	0.00	0 43	1.27	9.79	94,71
T226-135 3-2	chloritized biotite	10.67	1 13	10.26	0.07	15 40	0 11	6 55	0.02	0.05	0.50	7.75	52.51
T226-135 3-3	chlorite	24 55	0.05	22 14	0.03	20.64	0.20	17 27	0.04	0.00	0.01	0.07	85.00
T226-135.3-4	muscovite	47.12	0.45	33,70	0.09	0.79	0.00	0.96	0.02	0.34	1.00	10.29	94.77
T226-135.3-5	chloritized biotite	23.19	1.27	14.26	0.02	16.51	0.17	10.82	0.00	0.14	0.25	6.54	73.18
T226-135.3-6	muscovite	46.31	0.53	34.98	0.07	0.71	0.01	0.63	0.02	0.49	1.30	9.74	94.78
T226-135.3-7	muscovite	45.51	0.63	35.32	0.06	0.79	0.01	0.62	0.02	0.58	1.26	9.91	94.69
T226-135.3-8	biotite	35.98	1.59	19.55	0.05	16.11	0.11	11.41	0.02	0.00	0.48	9.64	94.95
T226-135.3-9	chlorite	27.84	0.41	19.98	0.08	23.93	0.24	13.84	0.10	0.00	0.02	1.64	88.07
T226-135.3-10	muscovite	45.40	0.60	35.37	0.06	0.77	0.02	0.62	0.00	0.31	1.24	9.87	94.25
T226-135.3-11	muscovite	45.55	0.55	35.31	0.10	0.82	0.00	0.60	0.01	0.31	1.27	9.89	94.40
T226-135.3-12	biotite	35.42	1.56	19.52	0.06	16.77	0.13	11.71	0.01	0.03	0.19	9.40	94.81
T226-135.3-13	chloritized biotite	32.59	1.87	18.76	0.08	18.48	0.12	12.41	0.61	0.26	0.24	6.59	92.00
T226-135.3-14	biotite	35.26	1.39	19.78	0.09	16.05	0.11	12.30	0.01	0.07	0.29	9.24	94.57
T226-135.3-15	muscovite	45.45	0.48	35.53	0.04	0.70	0.00	0.56	0.00	0.38	1.32	9.80	94.25
T221-42.5-1	chlorite	26.61	0.61	22.19	0.09	22.89	0.11	14.61	0.00	0.06	0.04	1.41	88.61
T221-42.5-2	chloritized biotite	33.00	1.77	19.05	0.12	20.57	0.10	12.25	0.01	0.10	0.09	6.86	93.95
T221-42.5-3	chloritized biotite	32.19	1.88	19.25	0.12	20.77	0.09	11.46	0.03	0.09	0.13	6.90	92.91
T221-42.5-4	chlorite	24.59	0.06	22.59	0.06	23.69	0.13	15.29	0.00	0.05	0.03	0.04	86.52
T221-42.5-5	muscovite	45,91	0.48	34.62	0.13	0.80	0.01	0.59	0.00	0.22	1.40	9.70	93.85
T221-42.5-6	muscovite	45.93	0.43	35.26	0.08	0.72	0.00	0.47	0.00	0.29	1.23	10.13	94.54
T221-42.5-7	muscovite	46.10	0.48	34.83	0.07	0.80	0.03	0.57	0.00	0.21	1.43	9.69	94.21
T221-42.5-8	muscovite	46.46	0.45	34.86	0.07	0.97	0.02	0.61	0.01	0.26	1.40	9.62	94.72
T221-42.5-9	biotite	34.91	1.73	19.45	0.09	19.13	0.09	10.35	0.03	0.05	0.24	9.05	95.12
T221-42.5-10	biotite	35.48	1.56	19.27	0.06	17.25	0.08	10.99	0.04	0.07	0.17	9.83	94.80
T221-42.5-11	biotite	35.54	1.27	19.17	0.10	16.95	0.09	11.24	0.04	0.00	0.26	9.75	94.39
T221-42.5-12	biotite	35.88	1.38	19.25	0.07	17.00	0.07	11.42	0.02	0.00	0.24	10.07	95.40
T221-42.5-13	biotite	35.55	1.5 <del>9</del>	19.25	0.12	17.37	0.07	11.46	0.02	0.33	0.22	9.77	95.74
T221-42.5-14	biotite	36.38	1.47	19.28	0.08	16.75	0.03	11.79	0.00	0.16	0.22	10.06	96.23
T221-42.5-15	biotite	35.07	1.32	19.37	0.04	17.83	0.08	11.97	0.03	0.31	0.17	9.11	95.30
T221-42.5-16	muscovite	46.25	0.58	35.68	0.10	0.77	0.00	0.62	0.02	0.25	1.35	9.67	95.29
T221-42.5-17	biotite	35.72	1.50	19.12	0.08	16.80	0.09	11.25	0.05	0.31	0.23	10.04	95.18
T221-42.5-18	muscovite	45.82	0.42	35.68	0.12	0.83	0.00	0.64	0.00	0.32	1.43	9.80	95.06

Sample	Comment	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO	BaO	Na <sub>2</sub> O	K₂O	Total
		%	%	%	%	%	%	%	%	%	%	%	
970705-3-1	biotite	36.93	1 41	19 35	0.06	15.19	0.06	12.36	0.01	0.02	0.08	10.48	95,94
970705-3-2	biotite	36.23	1.39	18.97	0.09	15.87	0.06	12.40	0.00	0.17	0.08	10.10	95,35
970705-3-3	biotite	36.10	1.40	19.26	0.06	16.07	0.04	12.62	0.01	0.00	0.07	9.85	95,47
970705-3-4	muscovite	46.00	0.60	35.12	0.12	0.93	0.00	0.61	0.00	0.51	1.23	10.08	95,20
970705-3-5	muscovite	46.12	0.65	34.46	0.07	0.94	0.01	0.65	0.00	0.32	1.22	10.13	94.57
970705-3-6	biotite	35.87	1.36	19.27	0.07	16.43	0.13	12.55	0.02	0.18	0.05	9.63	95.56
970705-3-8	biotite	36.76	1.27	19.66	0.10	15.35	0.10	12.41	0.01	0.20	0.04	10.61	96.49
970705-3-9	biotite	36.37	1.32	19.33	0.04	15.48	0.07	12.67	0.00	0.02	0.07	10,18	95.56
970705-3-11	muscovite	46.34	0.50	34.87	0.07	1.00	0.01	0.65	0.01	0.47	1.13	9.59	94.65
970705-3-12	muscovite	46.17	0.60	34.79	0.05	0.90	0.00	0,73	0.01	0.39	1.20	10.10	94.94
970705-3-13	muscovite	44.82	0.46	33.64	0.10	0.86	0.03	0.77	0.00	0.53	1.08	9.83	92.13
970705-3-14	biotite	36.08	1.39	18.93	0.05	15.26	0.08	12.31	0.02	0.02	0.08	10.17	94.36
970705-3-15	biotite	36.92	1.27	19.28	0.06	15.47	0.11	12.29	0.01	0.17	0.07	10.52	96.16
970705-3-16	chloritized biotite	34.10	0.96	18.87	0.04	15.50	0.09	13.63	0.16	0.11	0.05	7.06	90.58
970705-3-17	muscovite	46.31	0.47	34.81	0.09	0.76	0.02	0.65	0.00	0.41	1.14	10.19	94.84
970705-3-18	biotite	35.86	1.26	19.51	0.03	15.65	0.06	12.33	0.01	0.17	0.06	9.98	94.91
970705-3-19	biotite	36.43	1.42	19.04	0.04	15.44	0.06	12.20	0.02	0.21	0.07	10.37	95.28
970705-3-20	muscovite	45.47	0.50	34.14	0.08	0.81	0.00	0.60	0.01	0.45	1.12	9.65	92.82
970705-3-21	chlorite	26.84	0.05	23.26	0.02	17.92	0.15	16.41	0.43	0.02	0.58	0.03	85.71
970705-3-22	biotite	35.83	1.26	19.38	0.05	16.38	0.12	12.47	0.06	0.14	0.07	9.38	95.11
970705-3-23	biotite	35.62	1.40	19.34	0.10	15.78	0.07	12.29	0.01	0.04	0.07	10.14	94.85
970705-3-24	biotite	36.47	1.41	19.64	0.11	15.31	0.07	12.14	0.00	0.14	0.08	10.63	96.00
970705-3-25	biotite	35.79	1.40	19.42	0.12	15.56	0.09	12.35	0.02	0.31	0.05	10.33	95.44
970705-3-26	biotite	36.24	1.38	19.12	0.10	15.12	0.03	12.40	0.00	0.38	0.06	10.41	95.25
970705-3-27	biotite	35.80	1.38	<b>19.4</b> 1	0.04	15.53	0.10	11.86	0.02	0.25	0.08	10.51	94,97
970705-3-28	biotite	35.95	1.33	19.42	0.09	15.90	0.08	12.29	0.00	0.07	0.07	10.35	95.54
970705-3-29	biotite	36.11	1.40	19.38	0.09	15.71	0.09	12.29	0.00	0.29	0.08	10.29	95.73
970705-3-30	biotite	35.82	1.41	19.67	0.11	15.36	0.08	11.97	0.00	0.04	0.09	10.63	95.18
970705-3-31	biotite	35.51	1.35	19.36	0.05	15.60	0.10	12.21	0.00	0.10	0.06	10.18	94.51
970705-3-32	biotite	35.56	1.34	19.48	0.07	15.53	0.07	12.47	0.01	0.11	0.07	10.07	94.75
970705-3-33	biotite	35.98	1.40	19.52	0.05	15.25	0.07	12.42	0.01	0.04	0.03	10.45	95.22
970705-3-34	biotite	35.78	1.31	19.59	0.07	15.54	0.07	12.52	0.00	0.19	0.06	10.26	95.40
970705-3-35	biotite	35.77	1.36	19.49	0.09	15.64	0.06	12.76	0,00	0.31	0.06	9.97	95.50
970705-3-36	biotite	35.37	1.39	19.36	0.07	16.18	0.08	12.12	0.01	0.05	0.08	10.06	94,77
970705-3-37	muscovite	45.03	0.55	35.40	0.07	0.82	0.00	0.70	0.00	0.54	1.09	10.17	94.36
970705-3-38	muscovite	45.31	0.55	35.38	0.08	0.76	0.01	0.63	0.02	0.41	1.19	10.09	94.44
970705-3-39	biotite	35.44	1.43	19.35	0.08	15.36	0.08	11.99	0.01	0.11	0.05	10.32	94.21
970705-3-40	biotite	35.80	1.37	19.42	0.06	15.86	0.08	12.20	0.03	0.25	0.06	9.80	94.91
970705-3-41	biotite	35.90	1.45	19.46	0.02	15.68	0.06	12.10	0.00	0.00	0.10	10.34	95.11
970705-3-42	biotite	35.67	1.33	19.64	0.06	15.86	0.07	12.58	0.00	0.27	0.03	10.11	95.61

# Hemlo Plagioclase Probe Data (pelites)

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 20 nA; 20 s peak counts, except 45 s for Ba; 5 or 10 (for T226-182.5 and T221-42.5) um beam. Total Fe as Fe2O3 unless noted. Lower detection limits at 2SD are 0.01-0.02 wt %, except 0.04 wt% for BaO. Orthoclase-, albite, barite, spessartine and diopside-based standards for all major elements.

Comment	SiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	Fe <sub>2</sub> O <sub>3</sub> %	MgO %	MnO %	CaO	BaO	Na₂O	K₂O	Total
970720-5-1	60.41	25.06	0.00		70	70	70	%	%	%
970720-5-3	60.72	20.20	0.03	0.00	0.03	6.96	0.01	7.98	0.08	100.76
970720-5-4	60.72	25.08	0.01	0.00	0.02	6.55	0.00	8.01	0.05	100.43
970720-5-5	60.00	24.93	0.00	0.00	0.00	6.64	0.02	8.09	0.07	100.30
970720-5 6	00.93	24.82	0.04	0.00	0.01	6.57	0.04	8.14	0.06	100.60
970720 5 7	60.69	25.15	0.02	0.00	0.03	6.67	0.00	8.05	0.06	100.67
9/0/20-0-/	61.09	24.60	0.02	0.00	0.03	6.23	0.00	8.09	0.08	100.13
970720-5-8	60.51	25.22	0.00	0.00	0.04	6.62	0.02	7.92	0.10	100.10
9/0/20-5-9	61.33	24.73	0.02	0.00	0.02	6.27	0.01	8.18	0.07	100.41
9/0/20-5-10	60.79	25.02	0.02	0.00	0.03	6.65	0.00	7.96	0.06	100.02
9/0/20-5-11	60.90	25.03	0.01	0.00	0.01	6.54	0.01	7 92	0.00	100.02
9/0720-5-12	60.74	25.13	0.02	0.00	0.00	6 48	0.02	8.28	0.07	100.49
970720-5-13	60.68	25.19	0.04	0.00	0.00	6.61	0.02	9.20	0.11	100.77
970720-5-14	60.58	24.85	0.04	0.00	0.00	6.49	0.02	7.09	0.09	100.64
970720-5-15	60.95	24.90	0.01	0.00	0.00	6.61	0.00	7.90	0.09	100.03
970720-5-16	60.74	25.12	0.00	0.01	0.00	6.70	0.07	8.13	0.07	100.67
970720-5-17	60.76	24.98	0.00	0.01	0.02	0.72	0.02	8.06	0.09	100.76
970720-5-18	60.02	25.02	0.00	0.00	0.00	0.47	0.00	8.18	0.09	100.48
970720-5-19	60.35	25.02	0.00	0.01	0.00	6.53	0.00	7. <b>94</b>	0.10	99.60
970720-5-20	60.25	25.06	0.02	0.00	0.00	6.75	0.00	7.98	0.11	100.36
	50.20	20.00	0.00	0.01	0.01	6.51	0.00	7.94	0.11	99.87

Comment	SiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	Fe <sub>2</sub> O <sub>3</sub> %	MgO %	MnO %	<b>CaO</b> %	BaO %	Na₂O %	K₂O %	Total %
10-6-65.4-1	60.46	25.11	0.00	0.00	0.00	6 74	0.04			
10-6-65.4-2	60.52	25.27	0.05	0.00	0.00	0.74	0.04	7.97	0.05	100.37
10-6-65.4-3	61.04	24.97	0.30	0.00	0.00	0.74	0.03	7.92	0.05	100.58
10-6-65.4-4	59.16	26.60	0.00	0.00	0.00	0.20	0.03	8.09	0.19	100.86
10-6-65.4-5	60.25	25.60	0.06	0.07	0.02	4.12	0.16	7.24	2.35	99.98
10-6-65.4-6	60.30	25.04	0.06	0.02	0.00	7.03	0.06	1.11	0.04	100.83
10-6-65.4-7	60.47	25 17	0.00	0.01	0.00	6.74	0.03	7.81	0.07	100.06
10-6-65.4-8	60.63	25.35	0.04	0.00	0.00	0.00	0.01	8.02	0.07	100.43
10-6-65.4-9	60.60	25 18	0.04	0.02	0.00	0.03	0.01	7.72	0.05	100.70
10-6-65.4-10	60.32	25.24	0.01	0.00	0.02	0.78	0.01	7.92	0.07	100.58
10-6-65.4-11	60.53	25.03	0.03	0.00	0.00	6.84	0.02	7.96	0.07	100.53
10-6-65.4-12	60.21	25.00	0.04	0.00	0.01	6.78	0.05	7.86	0.08	100.37
10-6-65.4-13	60.95	25.05	0.07	0.00	0.00	0.83	0.02	7.79	0.07	100.05
10-6-65.4-14	60.92	25 19	0.07	0.00	0.00	6.51	0.05	7.85	0.06	100.54
10-6-65.4-15	60.12	25.37	0.00	0.00	0.00	6.34	0.07	8.12	0.08	100.76
10-6-65.4-16	60.66	24.96	0.02	0.00	0.01	6.93	0.04	7.86	0.12	100.47
10-6-65.4-17	60.98	24.00	0.04	0.00	0.00	0.36	0.04	8.07	0.08	100.21
		24.02	0.02	0.00	0.00	6.52	0.03	7.99	0.06	100.52
NGS51-1198.7-1	61.77	24 27	0.04	0.00	0.00	- F.A.				
NGS51-1198.7-2	61.06	24 74	0.11	0.00	0.00	5.51	0.00	8.48	0.07	100.13
NGS51-1198.7-3	60.92	24 68	0.07	0.01	0.00	6.24	0.02	8.25	0.05	100.49
NGS51-1198.7-4	62 16	24.32	0.07	0.00	0.00	6.18	0.02	8.05	0.04	99.95
NGS51-1198.7-5	60.63	24.02	0.07	0.00	0.00	5.58	0.05	8.56	0.05	100.80
NGS51-1198.7-6	60 74	25.00	0.14	0.00	0.00	6.08	0.07	8.10	0.07	99.79
NGS51-1198.7-6	61 45	23.00	0.11	0.01	0.00	6.30	0.02	8.05	0.04	100.28
NGS51-1198.7-7	61.40	25.39	0.09	0.00	0.00	5.40	0.00	8.43	0.06	99.42
	01.03	20.10	0.08	0.01	0.02	6.36	0.01	8.24	0.06	100.97

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Comment	SIO2	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	MnO	CaO	BaO	Na <sub>2</sub> O	K <sub>2</sub> O	Total
	%	%	%	%	%	%	%	%	%	%
T226-182.5-1	60.59	25.13	0.13	0.02	0.02	6 53	0.05	8 23	0.06	100.76
T226-182.5-2	61.03	25.04	0.09	0.00	0.00	6.42	0.00	8 16	0.00	100.70
T226-182.5-3	59.97	25.08	0.06	0.00	0.02	6.73	0.00	7.81	0.04	00.70
T226-182.5-4	60.45	25.02	0.04	0.00	0.00	6.62	0.00	8.19	0.07	99.11 100.26
T226-182.5-5	60.24	25.03	0.09	0.00	0.00	6.64	0.00	8.00	0.00	100.30
T226-182.5-6	60.16	24.79	0.19	0.00	0.00	6.59	0.00	8 15	0.09	100.09
T226-182.5-7	59.90	25.63	0.24	0.01	0.02	7.06	0.01	7 50	0.00	99.93 100 52
T226-182.5-8	60.65	25.23	0.10	0.00	0.02	6 68	0.05	8.00	0.00	100.55
T226-182.5-9	60.88	24.85	0.10	0.01	0.01	6 30	0.00	8.00	0.05	100.79
T226-182.5-10	60.79	25.08	0.43	0.00	0.04	6.50	0.02	8.20	0.00	100.41
T226-182.5-11	61.14	25.00	0.41	0.02	0.04	6.24	0.00	0.19	0.04	101.07
T226-182.5-12	61.89	24.19	0.16	0.00	0.04	5.53	0.02	0.30	0.05	101.25
T226-182.5-13	60.48	25.22	0.10	0.00	0.01	6.54	0.00	0.04	0.07	100.48
T226-182.5-14	60.59	25.19	0.23	0.00	0.00	6.56	0.04	0.01	0.06	100.45
T226-182.5-15	60.63	25.06	0.30	0.01	0.02	6.50	0.00	0.22	0.00	100.88
T226-182.5-16	60.48	25.17	0.12	0.00	0.03	6.68	0.01	0.09 7 Q4	0.06	100.69
						0.00	0.02	7.04	0.04	100.49
T226-235.3-1	61.04	24.50	0.04	0.00	0.02	5.56	0.01	8 27	0.06	90 18
T226-235.3-2	60.54	24.86	0.00	0.00	0.02	6.02	0.02	8 11	0.00	00.60
T226-235.3-3	60.51	24.55	0.04	0.00	0.02	5 70	0.02	8 38	0.04	99.02 00.26
T226-235.3-4	60.79	24.43	0.00	0.00	0.02	5.47	0.07	8.30	0.00	99.20
T226-235.3-5	60.62	24.86	0.00	0.00	0.02	6.08	0.02	8.29	0.07	99.07
T226-235.3-6	58.44	24.40	0.00	0.00	0.00	5.64	0.00	0.2 <del>3</del> 8.21	0.00	99.92 06.70
T226-235.3-7	60.83	24.62	0.02	0.00	0.03	5.61	0.00	8.25	0.08	90.78 99.43

Comment	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MaO	MnO	CaO	BaO	NaoO	K-0	Total
	%	%	%	%	%	%	%	%	%	%
T221-42.5-1	62.90	23.60	0.02	0.00	0.02	4,46	0.02	9.25	0.08	100.35
T221-42.5-2	62.94	23.34	0.05	0.00	0.00	4.32	0.02	9.05	0.08	99.80
T221-42.5-3	63.32	23.41	0.02	0.00	0.01	4.34	0.03	9.13	0.07	100.34
T221-42.5-4	63.29	23.48	0.00	0.00	0.00	4.40	0.00	9.00	0.07	100.24
T221-42.5-5	63.93	22.87	0.02	0.00	0.02	3.83	0.02	9.43	0.09	100.19
T221-42.5-6	63.26	22.99	0.02	0.00	0.00	3.83	0.02	9.37	0.07	99.57
T221-42.5-7	62.90	23.50	0.07	0.00	0.00	4.35	0.02	9.07	0.08	99.98

Plagioclase (pelite) 4

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### Hemlo Aluminosilicate (Kyanite) Probe Data

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 40 nA; 100 s peak counts, except 50 s for Fe and Mg, and 45 s for Si and Mn; 2 um beam. Total Fe as Fe2O3, V as V2O3, Sb as Sb2O3. Lower detection limits at 3-sigma 0.01 wt% for SiO2, Al2O3, and MgO; 0.02 wt% for V2O3, Sb2O3, Fe2O3 and MnO. Kyanite-based standard for major elements. c = core; i = intermediate; r = rim.

#### Weight Percent

Sample	m	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	Sb <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	Total
·		%	%	%	%	%	%	%	%
440NQ-34-4.3	4.3	37.00	61.81	0.04	0.01	0.58	0.00	0.00	99.44
440NQ-34-4.3	4.3	36.78	61.75	0.04	0.00	0.62	0.00	0.00	99.19
440NQ-34-4 3	4.3	36.81	61.73	0.03	0.01	0.57	0.00	0.00	99.16
440NQ-34-4 3	4.3	36.83	61.84	0.03	0.00	0.56	0.00	0.01	99.27
440NQ-34-4 3	4.3	37.02	62.03	0.05	0.00	0.78	0.00	0.01	99.88
440NQ-34-4.3	4.3	37.13	62.38	0.04	0.00	0.75	0.01	0.00	100.30
440NQ-34-4 3	4.3	37.15	62.45	0.03	0.00	0.60	0.00	0.00	100.22
440NO-34-4 3	43	37.27	62.72	0.02	0.00	0.44	0.00	0.01	100.46
440NO-34-4.3	43	37 17	62.40	0.06	0.00	0.67	0.00	0.01	100.31
440NO-34-4.3	43	37.05	62.50	0.03	0.00	0.53	0.00	0.00	100.11
440NQ-34-4.3	4.3	37.18	62.49	0.03	0.00	0.58	0.00	0.00	100.30
440NQ-34-4 3	4.3	37.29	62.55	0.03	0.00	0.44	0.00	0.01	100.34
440NO-34-4 3	43	36.94	61.85	0.04	0.00	0.56	0.01	0.00	99.40
440NQ-34-4.3	4.3	37.24	62.65	0.04	0.00	0.68	0.00	0.01	100.62

Sample	m	SiO <sub>z</sub> %	Al <sub>2</sub> O <sub>3</sub> %	V <sub>2</sub> O <sub>3</sub> %	Sb <sub>2</sub> O <sub>3</sub> %	Fe <sub>2</sub> O <sub>3</sub> %	MnO %	MgO %	Total %
440NQ-34-86.9	86.9	36.97	63.12	0.00	0.01	0.04	0.01	0.00	100.15
440NQ-34-86.9	86.9	36.96	63.12	0.01	0.01	0.04	0.00	0.00	100.15
440NQ-34-86.9	86.9	36.95	63.18	0.01	0.01	0.04	0.00	0.01	100.19
440NQ-34-86.9	86.9	36.63	62.52	0.02	0.00	0.03	0.00	0.00	99.21
440NQ-34-86.9	86.9	37.26	63.06	0.01	0.00	0.08	0.00	0.00	100.41
440NQ-34-86,9	86.9	36.99	63.07	0.03	0.00	0.04	0.00	0.01	100.13
440NQ-34-86.9	86.9	36.87	63.27	0.00	0.00	0.07	0.00	0.01	100.23
440NQ-34-86.9	86.9	36.90	63.16	0.02	0.00	0.02	0.00	0.00	100.10
440NQ-34-86.9	86.9	37.03	63.02	0.01	0.01	0.07	0.00	0.01	100.14
440NQ-34-86.9	86.9	37.17	62.78	0.02	0.01	0.19	0.00	0.00	100.16
440NQ-34-86.9	86.9	37.05	63.15	0.00	0.00	0.04	0.00	0.01	100.25
440NQ-34-86.9	86.9	36.78	62.65	0.01	0.00	0.26	0.00	0.02	99.72
440NQ-34-86.9	86.9	36.93	62.70	0.00	0.01	0.29	0.01	0.02	99.95
440NQ-34-86.9	86.9	37.31	63.04	0.00	0.00	0.11	0.00	0.01	100.47
440NQ-34-86.9	86.9	37.23	62.87	0.02	0.01	0.16	0.00	0.00	100.28
440NQ-34-86.9	86. <del>9</del>	37.39	62.89	0.02	0.00	0.13	0.00	0.00	100.42
440NQ-34-86.9	86.9	37.23	62.76	0.00	0.00	0.06	0.00	0.00	100.04
440NQ-34-86.9	86.9	37.14	62.84	0.00	0.00	0.05	0.00	0.00	100.04
440NQ-34-86.9	86.9	37.13	62.70	0.00	0.00	0.18	0.00	0.00	100.01
440NQ-34-86.9	86.9	37.04	62.80	0.02	0.00	0.25	0.00	0.02	100.13
440NQ-34-86.9	86.9	37.07	62.84	0.00	0.00	0.25	0.00	0.02	100.18
440NQ-34-86.9	86.9	36.82	62.75	0.02	0.00	0.26	0.01	0.02	99.88
440NQ-34-86.9	86.9	36.94	62.67	0.02	0.02	0.23	0.01	0.02	99.90

Sample	m	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	Sb <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	Total
		%	%	%	%	%	%	%	%
440NQ-34-88.5	88.5	37.01	62.63	0.00	0.00	0.36	0.00	0.00	100.01
440NQ-34-88.5	88.5	37.26	62.85	0.02	0.00	0.36	0.00	0.00	100.48
440NQ-34-88.5	88.5	37.34	62.49	0.01	0.01	0.44	0.00	0.01	100.30
440NQ-34-88.5	88.5	37.21	62.70	0.00	0.00	0.37	0.00	0.00	100.28
440NQ-34-88.5	88.5	37.57	63.06	0.00	0.01	0.40	0.00	0.00	101.03
440NQ-34-88.5	88.5	37.28	63.01	0.01	0.00	0.27	0.00	0.01	100.58
440NQ-34-88.5	88.5	37.15	62.85	0.02	0.00	0.48	0.00	0.01	100.51
440NQ-34-88.5	88.5	37.36	63.14	0.00	0.00	0.25	0.00	0.01	100.76
440NQ-34-94.2	94.2	37.25	62.63	0.03	0.01	0.32	0.00	0.01	100.24
440NQ-34-94.2	94.2	37.31	62.83	0.00	0.00	0.27	0.00	0.00	100.40
440NQ-34-94.2	94.2	37.27	62.84	0.01	0.00	0.27	0.00	0.00	100.40
440NQ-34-94.2	94.2	37.14	62.78	0.02	0.00	0.27	0.00	0.01	100.23
440NQ-34-94.2	94.2	37.03	62.75	0.01	0.01	0.27	0.00	0.00	100.06
440NQ-34-94.2	94.2	36.97	62.34	0.01	0.00	0.37	0.00	0.01	99.70
440NQ-34-94.2	94.2	37.18	62.77	0.00	0.00	0.21	0.01	0.00	100.17
440NQ-34-94.2	94.2	36.88	62.19	0.01	0.00	0.39	0.00	0.01	99.47
440NQ-34-94.2	94.2	37.28	62.79	0.00	0.00	0.24	0.00	0.00	100.32
440NQ-34-94.2	94.2	37.20	62.95	0.01	0.00	0.28	0.01	0.00	100.44
440NQ-34-94.2	94.2	37.34	62.70	0.01	0.00	0.41	0.00	0.01	100.47
440NQ-34-94.2	94.2	37.25	62.94	0.01	0.00	0.23	0.00	0.00	100.44

Sample	m	SiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	V <sub>2</sub> O <sub>3</sub> %	Sb <sub>2</sub> O <sub>3</sub> %	Fe <sub>2</sub> O <sub>3</sub> %	MnO %	MgO %	Total %
430-16-41.1	41.1	37.29	63.20	0.01	0.00	0.10	0.00	0.01	100.62
430-16-41.1	41.1	37.34	63.14	0.01	0.01	0.10	0.00	0.00	100.60
430-16-41.1	41.1	37.23	63.28	0.01	0.01	0.10	0.01	0.01	100.65
430-16-41.1	41.1	36.98	62.48	0.01	0.00	0.08	0.00	0.00	99.55
430-16-41.1	<b>41</b> .1	37.21	62.89	0.00	0.01	0.09	0.00	0.01	100.21
430-16-41.1	41.1	36.98	62.88	0.01	0.00	0.08	0.00	0.01	99.96
430-16-41.1	41.1	37.24	63.12	0.02	0.00	0.10	0.00	0.01	100.48
430-16-41.1	41.1	37.35	63.19	0.02	0.01	0.08	0.00	0.00	100.65
430-16-41.1	41.1	37.13	63.20	0.01	0.00	0.13	0.00	0.00	100.47
430-16-41.1	41.1	36,99	62.93	0.01	0.01	0.08	0.01	0.01	100.03
430-16-41.1	41.1	37.15	63.21	0.01	0.01	0.23	0.00	0.01	100.61
430-16-41.1	41.1	37.16	62.98	0.03	0.02	0.10	0.00	0.01	100.29
430-16-41.1	41.1	37.26	63.01	0.03	0.00	0.13	0.00	0.00	100.43
430-16-41.1	41.1	37.14	63.05	0.02	0.01	0.08	0.00	0.00	100.30
430-16-41.1	41.1	37.13	62.88	0.01	0.00	0.13	0.00	0.01	100.15
430-16-41.1	41.1	37.14	63.07	0.01	0.00	0.08	0.00	0.01	100.31
430-19-42.7	42.7	37.18	62.74	0.04	0.00	0.27	0.00	0.01	100.23
430-19-42.7	42.7	37.23	62.77	0.02	0.00	0.26	0.00	0.01	100.29
430-19-42.7	42.7	36.98	62.49	0.02	0.00	0.23	0.01	0.01	99.73
430-19-42.7	42.7	37.44	63.12	0.00	0.00	0.17	0.01	0.00	100.74
430-19-42.7	42.7	37.42	63.19	0.01	0.00	0.25	0.00	0.01	100.87
430-19-42.7	42.7	37.41	62.96	0.00	0.00	0.14	0.00	0.01	100.52
430-19-42.7	42.7	37.31	62.79	0.01	0.00	0.22	0.00	0.01	100.34
430-19-42.7	42.7	37.02	62.61	0.02	0.00	0.24	0.00	0.01	99.89

Sample	m	SiO <sub>2</sub> %	Al <sub>2</sub> O <sub>3</sub> %	V <sub>2</sub> O <sub>3</sub> %	Sb <sub>2</sub> O <sub>3</sub> %	Fe <sub>2</sub> O <sub>3</sub> %	MnO %	MgO %	Total %
430-19-42.7	42.7	37.40	62.73	0.02	0.01	0.31	0.00	0.02	100.49
430-19-42.7	42.7	37.16	62.70	0.04	0.00	0.31	0.01	0.02	100.23
430-19-42.7	42.7	37.43	62.94	0.03	0.00	0.35	0.01	0.02	100.78
430-19-42.7	42.7	37.14	62.54	0.03	0.00	0.36	0.00	0.02	100.08
430-19-42.7	42.7	37.12	62.55	0.03	0.00	0.36	0.00	0.01	100.07
430-19-42.7	42.7	37 01	62.61	0.02	0.00	0.26	0.00	0.01	99.91
430-19-42 7	42.7	37 26	62.80	0.02	0.00	0.30	0.00	0.02	100.39
430-19-42.7	42.7	37.27	62.78	0.02	0.00	0.24	0.00	0.01	100.31
430-19-42.7	42.7	37.15	62.65	0.03	0.00	0.24	0.00	0.01	100.08
10-6-63.0	63.0	37.24	62.86	0.02	0.01	0.09	0.00	0.00	100.22
10-6-63.0	63.0	37.38	63.09	0.03	0.00	0.10	0.00	0.01	100.60
10-6-63.0	63.0	37.39	62.91	0.07	0.00	0.22	0.00	0.01	100.59
10-6-63.0	63.0	37.19	62.87	0.03	0.00	0.19	0.00	0.00	100.28
10-6-63.0	63.0	37.37	62.87	0.02	0.00	0.12	0.00	0.00	100.39
10-6-63.0	63.0	37.27	62 46	0.02	0.00	0.14	0.01	0.00	99,90
10-6-63.0	63.0	37 39	63 00	0.03	0.00	0.15	0.00	0.00	100.56
10-6-63.0	63.0	37.33	63.05	0.03	0.00	0.12	0.00	0.00	100.54
10-6-63.0	63.0	37.31	62.94	0.01	0.00	0.11	0.00	0.00	100.38
10-6-63.0	63.0	37.44	62.77	0.04	0.00	0.21	0.00	0.02	100.49

## Hemlo Staurolite Probe Data

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 20 nA; 20 s peak counts; 5 um beam; high-precision quantitative data. Total Fe as Fe2O3 unless noted. Lower detection limits at 2SD are 0.01-0.02 wt %.

Orthoclase-, albite, barite, kyanite, spessartine, garnet, TiO2, ZnS, and diopside-based standards for all major elements. t = traverse, c = core, r = rim

Sample	Comment	SIO <sub>2</sub> %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	FeO %	MgO %	CaO %	MnO %	Na₂O %	K₂O %	ZnO %	Total
5-14-58.8	t	28.34	0.66	54 89	12 65	1 1 1	0.02	0.40	0.00	0.00		
5-14-58.8	t	28.02	0.63	54 47	12.00	1.41	0.02	0.10	0.00	0.00	0.33	98.40
5-14-58.8	t	28.02	0.00	54.47	13.92	1.00	0.00	80.0	0.00	0.02	0.33	99.02
5 14 59 9		20.07	0.05	54.59	14.13	1.53	0.01	0.11	0.02	0.01	0.39	99.50
5-14-50.0	L	28.08	0.62	54.34	14.10	1.53	0.00	0.11	0.01	0.01	0.37	99.16
5-14-58.8	t	28.07	0.62	54.85	13.61	1.51	0.00	0.08	0.00	0.03	0.33	99.10
5-14-58.8	t	27.87	0.62	55.06	13 07	1 28	0.00	0.10	0.00	0.00	0.00	99.10
5-14-58.8	t	28.24	0.61	54 67	13.28	1.20	0.00	0.10	0.00	0.02	0.38	98.40
5-14-58.8	t	28.20	0.65	54.67	12.50	1.52	0.00	0.10	0.01	0.01	0.38	98.82
5-14 59 9		20.20	0.05	54.67	13.38	1.55	0.00	0.11	0.01	0.01	0.31	99.10
5-14-00.0	L	28.34	0.64	55.21	12.49	1.18	0.00	0.06	0.00	0.02	0.34	98.27
5-14-58.8	r	28.07	0.64	55.33	12.97	1.65	0.01	0.08	0.01	0.02	0.27	99.05
5-14-58.8	Г	27.96	0.56	54.58	13.99	1 74	0.00	0.08	0.01	0.02	0.27	00.00
5-14-58.8	r	27.73	0.65	54 71	13.02	1.90	0.00	0.00	0.01	0.03	0.39	99.34
5-14-58.8	Ċ	27.06	0.00	64.64	10.02	1.00	0.00	0.08	0.02	0.01	0.35	98.36
5 14 59 9	C A	27.90	0.04	54.51	13.47	1.89	0.01	0.09	0.01	0.03	0.37	98.99
5-14-50.0	C	27.86	0.64	54.90	13.18	1.62	0.00	0.10	0.01	0.02	0.40	98.73
5-14-58.8	r	28.22	0.62	55.55	12.43	1.47	0.00	0.08	0.01	0.00	0.40	08 78
5-14-58.8	r	27.79	0.59	54.47	12.64	1.59	0.00	0.06	0.00	0.02	0.35	97.50

Sample	Comment	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Na₂O	K₂O	ZnO	Total
		%	%	%	%	%	%	%	%	%	%	
9-6-444.0	r	27.73	0.61	53.98	13.41	1.60	0.00	0.07	0.00	0.01	0.27	07 70
9-6-444.0	r	27.90	0.74	53.81	13.92	2.08	0.00	0.07	0.00	0.01	0.27	97.70
9-6-444.0	r	27.68	0.68	53,44	14.01	2.10	0.00	0.00	0.00	0.02	0.27	90.01
9-6-444.0	С	27.93	0.80	53.69	14.07	1.99	0.00	0.00	0.00	0.02	0.25	90.22
9-6-444.0	С	27.61	0.76	53.66	13.87	2.10	0.00	0.06	0.00	0.01	0.20	90.04 00.24
9-6-444.0	r	27.67	0.62	53.37	13.73	2 15	0.00	0.00	0.00	0.01	0.24	90.31
9-6-444.0	r	27.92	0.68	53.34	13 87	2.10	0.00	0.07	0.00	0.02	0.30	97.92
9-6-444.0	С	28.03	0.75	53.74	13.77	2 20	0.01	0.00	0.00	0.02	0.29	98.29
9-6-444.0	С	28.00	0.70	53.54	13.69	2.18	0.01	0.07	0.02	0.02	0.34	90.90
9-6-444.0	r	27.75	0.57	53.86	13.61	1.98	0.01	0.00	0.00	0.01	0.29	90.49
9-6-444.0	r	28.07	0.62	54.27	13 44	1.69		0.07	0.00	0.02	0.31	90.10
9-6-444.0	r	27.84	0.60	53.92	14 01	2 17	0.00	0.00	0.02	0.02	0.34	90.03
9-6-444.0	r	27.85	0.46	54.19	13.98	1.87	0.00	0.00	0.03	0.01	0.27	98.94
							0.01	0.07	0.02	0.02	0.27	90.73
T95-3-6.9	r	28.14	0.54	54.62	13.45	1.97	0.00	0.16	0.01	0.02	0 12	00.05
T95-3-6.9	r	27.73	0.59	54.60	13.53	2.08	0.00	0.10	0.01	0.02	0.15	99.00
T95-3-6.9	С	27.57	0.58	54.60	13.57	2.03	0.00	0.14	0.01	0.00	0.15	90.03
T95-3-6.9	С	27.84	0.63	54.61	13.77	2.00	0.00	0.10	0.00	0.02	0.09	90.07
T95-3-6.9	t	27.86	0.64	54.67	13 16	2.06	0.00	0.10	0.02	0.02	0.13	99.22
T95-3-6.9	t	27.70	0.61	54.71	13.58	2.00	0.00	0.12	0.01	0.02	0.11	98.00
T95-3-6.9	t	27.48	0.56	54.57	13.65	2.06	0.00	0.14	0.01	0.02	0.10	98.98
T95-3-6.9	t	27.86	0.58	54.35	13 73	2.06	0.00	0.10	0.01	0.00	0.14	90.01
T95-3-6.9	t	27.82	0.55	54 14	13.53	2.00	0.00	0.10	0.02	0.01	0.14	98.87
T95-3-6.9	t	27.51	0.60	54 49	13.69	2.12	0.00	0.14	0.00	0.01	0.13	98.42
T95-3-6.9	t	27.72	0.58	54 37	13.65	2.01	0.01	0.14	0.00	0.01	0.16	98.61
T95-3-6.9	t	27.74	0.57	54.62	13.62	2.00	0.00	0.14	0.00	0.01	0.10	98.68
T95-3-6.9	t	27.67	0.59	54 53	13.51	2.10	0.00	0.13	0.01	0.00	0.13	98.91
T95-3-6.9	t	27.91	0.61	54 56	13.54	2.00	0.00	0.14	0.00	0.00	0.15	98.67
T95-3-6.9	ť	27.87	0.60	54 97	12 73	2.07	0.00	0.10	0.00	0.01	0.16	99.02
	-		0.00	04.01	12.10	2.02	0.00	0.15	0.00	0.01	0.12	98.48

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Sample	Comment	SiO₂ %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	FeO %	MgO %	CaO %	MnO %	Na₂O %	K₂O %	ZnO %	Total
T95-3-6.9	t	27.68	0.63	54.63	13.22	2.10	0.00	0.14	0.02	0.02	0.15	98 58
T95-3-6.9	r	28.09	0.58	54.60	13.21	2.05	0.00	0.14	0.01	0.01	0.16	98.84
T95-3-6.9	r	27.50	0.55	54.34	13.47	2.01	0.00	0.15	0.00	0.01	0.10	08.17
T95-3-6.9	С	27.32	0.58	54.44	13.54	2.01	0.01	0 14	0.00	0.01	0.14	08.19
T95-3-6.9	С	27.76	0.60	54.75	13.26	2.06	0.00	0.12	0.00	0.03	0.14	98.70
10-6-65.4	с	28.15	0.76	55.20	12.07	1.36	0.00	0.11	0.02	0.01	0.17	97.84
10-6-65.4	r	27.93	0.68	54.79	12.40	2.19	0.00	0.10	0.00	0.00	0 17	98 25
10-6-65.4	С	28.16	0.68	55.65	12.16	1.67	0.00	0.08	0.00	0.02	0.20	98.61
10-6-65.4	С	27.83	0.64	55.88	12.10	1.62	0.00	0.08	0.00	0.00	0.16	98.32
10-6-65.4	г	28.05	0.74	54.97	11.67	1.29	0.00	0.09	0.00	0.00	0.19	97.00
10-6-65.4	С	28.10	0.61	55.63	12.46	1.50	0.00	0.09	0.01	0.01	0.19	98.60
10-6-65.4	r	27.73	0.36	56.37	12.23	1.15	0.00	0.10	0.01	0.01	0.10	Q8 16
10-6-65.4	С	28.10	0.56	55.22	12.07	1.52	0.00	0.07	0.02	0.01	0.17	97 73
10-6-65.4	r	27.74	0.71	55.44	11.73	1.66	0.01	0.06	0.03	0.01	0.60	97 99
10-6-65.4	С	28.22	0.61	54.88	12.14	1.83	0.00	0.06	0.00	0.02	0.59	98.34
10-6-65.4	С	27.87	0.66	54.39	12.75	1.93	0.00	0.05	0.00	0.02	0.65	98.32
10-6-65.4	r	27.80	0.58	54.84	11. <del>9</del> 7	1.56	0.00	0.05	0.02	0.01	0.63	97 45
10-6-65.4	t	28.33	0.64	55.43	11.46	1.65	0.00	0.06	0.01	0.02	0.16	97 76
10-6-65.4	t	28.22	0.65	55.30	11.34	1.91	0.00	0.07	0.00	0.01	0.17	97.67
10-6-65.4	t	28.12	0.76	55.01	11.15	2.09	0.00	0.05	0.00	0.02	0.16	97.37
10-6-65.4	t	28.24	0.74	55.01	11.43	2.11	0.00	0.04	0.00	0.02	0.10	97 74
10-6-65.4	t	28.10	0.67	55.38	11.59	1.72	0.00	0.06	0.00	0.00	0.14	97.66
10-6-65.4	t	28.08	0.64	55.27	11.56	1.69	0.01	0.08	0.01	0.01	0.17	97.52
10-6-65.4	t	27.96	0.62	55.34	11.84	1.93	0.00	0.06	0.01	0.01	0 14	97 92
10-6-65.4	t	27.93	0.80	54.79	12.40	1.86	0.01	0.07	0.02	0.02	0.15	98.06

Sample	Comment	SIO2	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Na <sub>2</sub> O	K₂O	ZnO	Total
		%	%	%	%	%	%	%	%	%	%	
440NQ34-4.3	r	27.69	0.66	55.58	11.11	0.94	0.02	0.56	0.01	0.01	0.08	96.67
440NQ34-4.3	С	28.12	0.68	54.84	11.66	1.11	0.01	0.59	0.00	0.00	0.05	97.05
440NQ34-4.3	t	28.18	0.66	55.47	10.95	1.01	0.01	0.51	0.01	0.02	0.09	96.89
440NQ34-4.3	t	28.16	0.66	55.34	11.46	1.05	0.00	0.56	0.01	0.02	0.09	97.34
440NQ34-4.3	t	28.11	0.65	56.02	11.53	1.01	0.00	0.61	0.01	0.02	0.10	98.05
440NQ34-4.3	t	28.13	0.66	55.05	11.69	1.03	0.00	0.62	0.02	0.01	0.08	97.29
440NQ34-4.3	t	28.03	0.68	55.21	11.61	1.00	0.00	0.59	0.00	0.01	0.05	97.18
440NQ34-4.3	r	27.92	0.70	55.06	11.46	0.85	0.02	0.56	0.00	0.01	0.10	96.69
440NQ34-4.3	С	27.83	0.70	55.32	11.71	0.95	0.00	0.59	0.00	0.00	0.06	97.16
440NQ34-4.3	r	27.91	0.69	55.03	11.78	0.97	0.00	0.59	0.00	0.01	0.13	97.11
440NQ34-4.3	С	28.11	0.70	55.09	12.00	1.09	0.00	0.59	0.02	0.01	0.09	97.68
440NQ34-4.3	r	27.72	0.66	54.73	11.79	1.14	0.03	0.59	0.00	0.01	0.09	96.76
440NQ34-4.3	C	28.17	0.69	54.81	11.72	1.26	0.01	0.58	0.02	0.01	0.10	97.36
T226-15	t	27.88	0.59	54.49	12.14	1.52	0.01	0.17	0.03	0.01	0.24	97.08
T226-15	t	27.88	0.61	54.12	13.19	1.83	0.01	0.17	0.00	0.01	0.29	98.11
T226-15	t	27.74	0.60	54.61	12.68	1.63	0.00	0.16	0.00	0.01	0.29	97.72
T226-15	t	27.91	0.58	54.65	12.59	1.68	0.00	0.17	0.00	0.01	0.26	97.85
T226-15	t	27.68	0.56	54.46	13.48	1.63	0.00	0.17	0.01	0.02	0.25	98.24
T226-15	t	27.69	0.51	55.37	12.54	1.39	0.00	0.15	0.00	0.01	0.28	97.93
T226-15	t	27.63	0.66	54.29	13.32	1.81	0.00	0.18	0.00	0.02	0.21	98.12
T226-15	t	27.68	0.64	54.49	12.81	1.57	0.00	0.15	0.00	0.01	0.22	97.56
T226-15	t	27.61	0.59	54.65	12.21	1.70	0.01	0.16	0.01	0.02	0.19	97.15
T226-15	t	28.10	0.59	54.80	12.21	1.19	0.00	0.21	0.02	0.01	0.26	97.39
T226-15	г	27.75	0.60	54.76	12.43	1.76	0.00	0.16	0.02	0.01	0.23	97.72
T226-15	С	27.74	0.61	54.29	13.19	1.63	0.00	0.15	0.00	0.02	0.23	97.86
T226-15	r	27.67	0.61	54.25	13.21	1.92	0.00	0.18	0.00	0.02	0.25	98.10
T226-15	с	27.42	0.64	53.14	13.14	1.73	0.00	0.20	0.02	0.00	0.27	96.56
T226-15	r	27.76	0.56	55.01	11.89	1.54	0.00	0.19	0.00	0.01	0.16	97.11
T226-15	С	27.75	0.59	54.10	13.41	1.81	0.00	0.20	0.01	0.02	0.22	98.09

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Sample	Comment	SIO <sub>2</sub> %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	FeO %	MgO %	CaO %	MnO %	Na₂O %	K₂O %	ZnO %	Total
T221-224.6	r	27.57	0.58	54.86	13.44	1.13	0.00	0.21	0.00	0.02	0.12	97,93
T221-224.6	С	27.59	0.60	54.31	13.46	1.67	0.00	0.19	0.00	0.01	0.14	97.96
T221-224.6	t	27.45	0.61	54.63	13.77	1.65	0.01	0.21	0.00	0.01	0.11	98.44
T221-224.6	t	27.77	0.57	54.36	13.68	1.78	0.00	0.19	0.01	0.02	0.10	98.47
T221-224.6	t	27.66	0.65	54.16	13.71	1.82	0.00	0.19	0.00	0.02	0.10	98 30
T221-224.6	t	27.34	0.56	54.18	13.75	1.82	0.01	0.19	0.00	0.02	0.11	97 97
T221-224.6	t	27.44	0.58	54.34	13.72	1.79	0.00	0.19	0.00	0.02	0.09	98.18
T221-224.6	t	27.25	0.57	54.33	13.71	1.68	0.00	0.18	0.00	0.02	0.08	97.82
T221-224.6	t	27.37	0.54	54.33	13.84	1.63	0.00	0.20	0.01	0.02	0.12	98.05
T221-224.6	t	27.54	0.68	54.32	13.74	1.80	0.01	0.20	0.01	0.02	0.10	98.41
T221-224.6	t	27.65	0.61	54.29	13.52	1.80	0.00	0.17	0.00	0.01	0.13	98.17
T221-224.6	r	27.69	0.58	54.22	13.35	1.80	0.00	0.21	0.01	0.01	0.11	97.97
T221-224.6	С	27.35	0.57	54.47	13.68	1.77	0.01	0.19	0.00	0.01	0.11	98.15
T221-224.6	r	27.44	0.59	54.14	13.57	1.78	0.01	0.21	0.02	0.01	0.12	97.88
T221-224.6	С	27.84	0.59	54.26	13.96	1.81	0.00	0.19	0.02	0.01	0.12	98.81
8-35-173.5	t	27.28	0.75	55.07	12.51	1.49	0.00	0.09	0.01	0.01	0.37	97.58
8-35-173.5	t	27.70	0.69	54.11	13.41	1.77	0.01	0.11	0.01	0.02	0.36	98.16
8-35-173.5	t	27.93	0.69	54.39	12.70	1.72	0.00	0.12	0.00	0.00	0.35	97.90
8-35-173.5	t	27.71	0.63	55.16	12.78	1.34	0.00	0.13	0.02	0.01	0.39	98.17
8-35-173.5	r	28.18	0.66	55.15	11.45	1.30	0.01	0.13	0.01	0.02	0.40	97.30
8-35-173.5	С	28.07	0.64	54,78	11.81	1.71	0.00	0.12	0.01	0.01	0.29	97 42
8-35-173.5	t	27.67	0.73	55,65	11.85	1.34	0.01	0.10	0.01	0.01	0.35	97 71
8-35-173.5	t	27.47	0.66	54.37	13.40	1.51	0.00	0.11	0.00	0.01	0.36	97 90
8-35-173.5	t	27.78	0.65	54.18	12.88	1.45	0.00	0.10	0.03	0.01	0.34	97 40
8-35-173.5	t	27.78	0.62	54.76	12.38	1.55	0.01	0.10	0.01	0.01	0.37	97 60

# Appendix II

Electron microprobe analyses of metabasites

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## Hemlo Amphibole Probe Data

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 20 nA; 20 s peak counts; 5 um beam.

Total Fe as FeO. Lower detection limits at 2SD are 0.01-0.02 wt %.

Orthoclase-, albite, spessartine, garnet, TiO2 and diopside-based standards for all major elements.

Sample #	SiO <sub>2</sub> %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	Cr <sub>2</sub> O <sub>3</sub> %	FeO %	MgO %	MnO %	CaO %	Na₂O %	K₂O %	Total
971007_7-3	44.15	0.49	10.35	0.01	18.21	10.17	0.36	11.73	1 25	0.97	97 74
971007_7-4	43.16	0.57	10.95	0.06	18.54	9.68	0.34	11.81	1 27	1 02	97 AA
971007_7-5	43.61	0.50	10.49	0.04	18.13	9.91	0.31	11.96	1 27	0.93	97.19 97.19
971007_7-6	43.04	0.55	11.02	0.08	18.62	9.60	0.31	11 72	1.34	0.00	97.13
971007_7-9	43.63	0.47	10.43	0.03	18.45	9.82	0.33	11.89	1.04	0.07	07 25
971007_7-10	42.93	0.58	10.99	0.04	18.61	9.45	0.28	11.00	1.27	1.05	97.00
971007_7-12	42.96	0.52	10.84	0.04	18.93	9.51	0.34	11 78	1.37	1.00	97.0Z
971007_7-13	42.72	0.57	11.09	0.00	18.70	9.34	0.36	11.70	1.32	1.02	97.22
971007_7-14	37.96	0.16	24.27	0.06	10.41	0.04	0.00	23.41	0.01	0.00	97.01
971007_7-15	38.26	0.16	24.71	0.00	9.78	0.04	0.18	23.43	0.01	0.00	90.00
971007_7-17	38.06	0.14	24.52	0.06	9.84	0.02	0.10	20.40	0.00	0.00	90.00
971007_7-19	43.51	0.50	10.66	0.01	18.23	9.69	0.34	12 00	1 22	0.00	90.31
971007_7-41	43.26	0.58	10.55	0.00	18.37	9.78	0.30	11.82	1.22	0.90	97.00
971007_7-42	44.14	0.43	10.21	0.00	18.17	10.02	0.33	11 01	1.27	0.97	07 44
971007_7-43	42.95	0.55	11.00	0.07	18 74	9.45	0.00	11.51	1.24	0.90	97.44
971007_7-44	44.27	0.47	10.04	0.00	18.01	10.08	0.20	11.07	1.04	0.90	97.05
971007_7-45	43.74	0.51	10.21	0.00	18 15	9.84	0.00	11.75	1.20	0.09	97.10
971007_7-46	44.13	0.50	9.91	0.00	18 18	0.04	0.32	11.00	1.00	0.91	90.98
971007_7-47	43.80	0.53	10.26	0.05	18.36	9.90	0.33	11.05	1.30	0.91	97.13
971007_7-50	43.69	0.49	10.27	0.01	18.68	9.87	0.30	11.87	1.23	0.91	97.17 97.46

Sample #	SiO₂ %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	Cr <sub>2</sub> O <sub>3</sub> %	FeO %	MgO %	MnO %	CaO %	Na₂O %	K₂O %	Total
971008_1-1	46.56	0.42	8.53	0.11	13 35	13.46	0.33	12 10	4.20	0.00	
971008_1-2	45.31	0.36	9,46	0.06	13.60	13.40	0.00	12.10	1.30	0.68	97.00
971008_1-3	45.89	0.36	9.43	0.00	13 70	13.00	0.00	12.10	1.53	0.74	96.62
971008_1-4	46.17	0.38	8.93	0.15	13.28	13.23	0.29	12.00	1.61	0.57	97.41
971008_1-5	54.31	0.06	2.38	0.10	9.34	17.06	0.30	12.13	1.52	0.70	97.10
971008_1-6	52.49	0.13	373	0.00	10 55	16.50	0.32	12.90	0.30	0.10	97.85
971008_1-7	43.74	0.44	10.62	0.00	15.01	10.02	0.34	12.67	0.49	0.29	97.27
971008_1-8	45.40	0.36	9.58	0.04	13.01	12.20	0.35	12.09	1.61	1.09	97.29
971008_1-18	43.81	0.51	10 41	0.00	15.02	12.97	0.33	12.23	1.65	0.54	97.05
971008_1-19	53,30	0.01	2.87	0.07	10.42	17.05	0.33	12.03	1.60	1.13	97.08
971008 1-20	54.33	0.04	1 36	0.00	10.23	17.00	0.29	12.46	0.47	0.15	96.93
971008 1-21	45.02	0.43	9.55	0.01	10.31	17.13	0.30	12.58	0.24	0.08	96.39
971008 1-22	43.74	0.51	10.65	0.01	14.45	12.48	0.32	12.01	1.58	0.73	96.67
971008 1-23	43.55	0.51	10.00	0.00	15.24	11.85	0.29	11.86	1.72	1.09	97.09
		0.01	10.01	0.00	15.30	11.64	0.26	11.96	1.57	1.05	96.86
971009_9-1	43.29	0.42	11 09	0.04	17 17	10 22	0.20	44.07		• • •	
971009_9-2	44.74	0.40	9.97	0.04	16 45	10.33	0.32	11.67	1.31	0.93	96.63
971009_9-3	44.73	0.47	973	0.00	16.65	11.10	0.30	11.81	1.25	0.78	96.96
971009_9-4	44.75	0.50	9.69	0.01	16.00	10.00	0.29	11.92	1.22	0.76	96.99
971009_9-5	43.94	0.49	10.00	0.00	17.32	10.90	0.26	11.98	1.17	0.79	97.11
971009_9-6	43.33	0.54	10.10	0.00	17.50	10.03	0.34	11./1	1.28	0.88	96.81
971009 9-7	43.95	0.49	10.00	0.04	17.01	10.31	0.33	11.65	1.31	0.97	96.99
971009 9-8	43 24	0.40	10.24	0.02	17.3/	10.53	0.32	11.83	1.21	0.90	96.91
971009 9-16	43.08	0.02	11 20	0.07	17.49	10.39	0.34	11.88	1.36	1.06	97.53
971009 9-17	43.81	0.40	10.79	0.03	17.50	10.11	0.30	11.64	1.44	1.11	97.03
971009 9-18	49.78	0.24	4 82	0.00	17.21	10.44	0.30	11.71	1.42	0.92	97.15
971009 9-19	43 50	0.41	10 97	0.04	17.00	11.91	0.40	11.83	0.74	0.48	97.35
	70.00	0.44	10.07	0.01	17.52	10.20	0.30	11.55	1.42	0.98	96.87

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Sample #	SiO₂ %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	Cr₂O₃ %	FeO %	MgO %	MnO %	CaO %	Na₂O %	K₂O %	Total
T226-28.8-4	42.71	0.81	10.24	0.00	19 30	9.38	0.53	11 24	1 50	0.75	00 74
T226-28.8-5	42.05	0.88	10.64	0.00	19 16	9.24	0.00	11.04	1.00	0.75	96.74
T226-28.8-6	43.24	0.84	9.67	0.05	19.45	9.35	0.51	11.24	1.00	0.78	96.42
T226-28.8-7	42.73	0.81	10.13	0.00	18.79	9.50	0.54	11.40	1.04	0.74	97.03
T226-28.8-8	43.39	0.87	9.82	0.00	19.34	9.50	0.01	11.04	1.04	0.71	96.54
T226-28.8-9	44.74	0.72	8.78	0.00	18.41	10 30	0.40	14.00	1.41	1.00	97.50
T226-28.8-10	43.08	0.82	9.89	0.07	19.31	0.59	0.40	11.33	1.33	0.83	97.16
T226-28.8-11	43.42	0.79	9.82	0.00	19.33	9.51	0.47	11.20	1.54	1.01	97.05
T226-28.8-18	44.98	0.66	8.51	0.00	17.81	10.75	0.40	11.40	1.46	0.99	97.46
T226-28.8-19	42.94	0.62	10.13	0.01	19.97	0.75	0.40	11.41	1.31	0.81	96.86
		0.02	10.10	0.02	10.07	9.73	0.50	11.47	1.61	0.81	96.75
970709-1-1	41.46	0.50	15 21	0.06	19 72	6.64	0.26	10.00	4.50	0.54	
970709-1-2	52,99	0.18	20.68	0.00	6.06	2.20	0.30	10.99	1.58	0.51	97.15
970709-1-3	41.19	0.56	14 77	0.02	10.30	2.20	0.13	8.09	5.75	0.19	97.25
970709-1-4	41.22	0.52	15.24	0.00	19.74	0.00	0.38	10.90	1.58	0.51	96.58
970709-1-5	41.81	0.60	14 60	0.07	19.00	0.04	0.35	11.06	1.54	0.56	96.88
970709-1-6	41.57	0.54	14.00	0.04	19.01	0.09	0.34	11.11	1.48	0.48	97.01
970709-1-7	42.38	0.60	14.70	0.00	19.70	0.70	0.41	10.98	1.58	0.51	97.00
970709-1-8	42.85	0.50	13.71	0.00	19.07	7.00	0.43	10.84	1.59	0.49	97.47
970709-1-9	42.53	0.54	13.91	0.00	19.74	7.29	0.39	10.94	1.43	0.46	97.42
970709-1-10	43.16	0.52	13.66	0.00	10.07	1.21 7 AF	0.41	10.82	1.48	0.45	97.33
970709-1-11	42.10	0.54	14.78	0.00	20.22	7.40 6.95	0.41	11.06	1.54	0.43	98.20
970709-1-12	42.08	0.54	14.70	0.03	20.23	0.00	0.42	10.99	1.55	0.51	98.11
970709-1-13	42.05	0.62	14.00	0.00	19.00	7.10	0.41	11.16	1.52	0.50	97.70
970709-1-14	42 20	0.52	14.16	0.03	19.00	7.06	0.41	11.13	1.48	0.49	97.29
970709-1-15	41 76	0.50	14.10	0.02	19.09	1.17	0.41	11.02	1.48	0.48	97.48
970709-1-16	42 62	0.046	19.40	0.07	19.86	6.92	0.33	11.16	1.44	0.53	97.10
970709-1-18	42 25	0.40	17.04	0.00	19.64	7.19	0.36	11.20	1.41	0.44	96.93
	74.40	0.00	14.20	0.00	19.99	6.82	0.34	11.09	1.57	0.52	97.27

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Sample #	SiO₂ %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	Cr <sub>2</sub> O <sub>3</sub> %	FeO %	MgO %	MnO %	CaO %	Na₂O %	K₂O %	Total
970709-1-19	41.72	0.53	14.97	0.02	20.05	6.70	0.37	10.83	1.64	0.52	97 36
970709-1-20	42.58	0.51	13.60	0.03	19.73	7.22	0.39	11.06	1.40	0.43	97.02
970709-12-1	49.86	0.27	5.65	0.06	13.45	14 11	0.33	11 93	0.85	0.42	97.00
970709-12-2	46.47	0.43	8.48	0.03	15.32	12 38	0.32	11.60	1.26	0.72	97.00
970709-12-3	47.53	0.32	7.64	0.05	14.66	12.95	0.31	11.75	1 10	0.01	97.20
970709-12-4	47.60	0.32	7,59	0.03	14.57	12 98	0.31	11.75	1.10	0.70	06.80
970709-12-5	48.93	0.29	6.30	0.00	13.82	13 78	0.27	11.70	0.90	0.00	90.09 06.70
970709-12-6	49.54	0.27	5.54	0.04	13.38	14 21	0.33	11.86	0.30	0.01	90.70
970709-12-7	49.12	0.28	5,89	0.11	13.74	14.14	0.28	11.80	0.79	0.43	96.71
970709-12-8	49.64	0.19	5.54	0.04	13.59	14.61	0.33	11 99	0.87	0.40	97 20
970709-12-9	52.68	0.15	3.22	0.02	12.07	15.97	0.30	12 40	0.42	0.40	97.20
970709-12-10	48.41	0.30	6.50	0.03	14 21	13 55	0.34	12.00	0.42	0.53	06.94
970709-12-11	48.28	0.33	6,67	0.05	14.65	13 32	0.36	11.00	1 00	0.00	90.04
970709-12-12	48.56	0.29	6.33	0.00	14.11	13 55	0.32	12 07	0.97	0.00	06 77
970709-12-13	50.36	0.22	4,80	0.02	12.93	14 73	0.29	12.07	0.07	0.04	90.77
970709-12-14	47.95	0.30	6,55	0.05	14.02	13.61	0.33	11.82	0.70	0.00	96.02
970709-12-15	48.40	0.25	6.27	0.05	14.07	13.65	0.30	12 17	0.04	0.50	96.48
970709-12-16	45.93	0.37	8.20	0.05	15.34	12 28	0.32	11.89	1 04	0.01	06.33
970709-12-17	49.38	0.25	5,27	0.04	13.04	14 73	0.33	12 10	0.71	0.77	06.00
970709-12-18	46.24	0.43	7.78	0.08	15.14	12 55	0.30	11 91	1 13	0.33	90.21
970709-12-19	46.82	0.41	7.75	0.06	14.97	12.59	0.35	11.96	1.16	0.77	90.37
970709-12-20	47.61	0.32	6.82	0.06	14.21	13 35	0.31	11.80	n qq	0.62	06 1 2
970709-12-21	27.56	0.03	16.90	0.17	23.13	17.84	0.29	0.06	0.00	0.02	86.11

Sample #	SiO₂ %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	Cr <sub>2</sub> O <sub>3</sub> %	FeO %	MgO %	MnO %	CaO %	Na₂O %	K₂O %	Total
970709-11A-1	47.70	0.33	6.73	0.06	14.98	12.84	0.28	11 94	0.94	0.57	96.42
970709-11A-2	47.89	0.33	6,89	0.05	15.05	13.02	0.31	12.01	0.86	0.58	90.42
970709-11A-4	48.88	0.28	6.08	0.03	14.66	13.65	0.30	12.05	0.87	0.50	97.00
970709-11A-5	46.04	0.43	8.14	0.00	15.89	12.26	0.31	11.82	1.12	0.74	96.80
970709-11A-6	48.46	0.27	6.19	0.07	14.34	13.59	0.31	12 22	0.76	0.50	96.74
970709-11A-7	47.14	0.37	7.16	0.07	15.22	12.95	0.30	12.09	1 04	0.00	07.01
970709-11A-8	48.57	0.27	5.97	0.10	14.45	13.49	0.30	12.00	0.74	0.04	97.01
970709-11A-9	47.27	0.35	7.22	0.05	15.30	12.88	0.29	12.00	0.98	0.64	97.04
970709-11A-10	49.44	0.27	5.60	0.03	14.17	13.99	0.28	12.23	0.72	0.46	97.04
970709-11 <b>A-</b> 11	46.43	0.42	7.52	0.05	15.40	12.41	0.27	11.95	1.01	0.69	96.21
981005-6-1	44.88	0.51	10.11	0.00	16.45	10.90	0.42	11.87	1 01	0 92	97 12
981005-6-2	44.30	0.54	10.56	0.00	16.84	10.53	0.37	11 91	1 11	0.02	97.12
981005-6-3	43.37	0.61	11.28	0.01	17.40	10.16	0.38	11 91	1 20	1.04	97.20
981005-6-4	44.55	0.55	10.42	0.00	16.56	10.78	0.41	11.82	1 11	1.01	97.24
981005-6-5	43.96	0.61	10.82	0.01	17.18	10.46	0.35	11.83	1.17	0.98	97 43
981005-6-6	44.50	0.55	10.53	0.04	16.37	10.80	0.38	12.01	1 14	0.94	97.30
981005-6-7	37.87	0.12	23.99	0.03	10.40	0.04	0.13	23.40	0.02	0.01	96.06
981005-6-8	38.10	0.11	24.60	0.02	9.76	0.05	0.23	23.35	0.02	0.00	96 25
981005-6-9	43.97	0.58	10.95	0.04	16.81	10.65	0.42	11.82	1.19	1.02	97 47
981005-6-10	44.23	0.54	10.85	0.04	17.04	10.59	0.38	11.90	1.13	1 00	97 71
981005-6-11	43.34	0.62	11.35	0.04	17.14	10.31	0.40	11.90	1.18	1.06	97 33
981005-6-12	44.40	0.55	10.97	0.01	16.86	10.82	0.41	11.90	1.26	0.84	98.04
981005-6-13	44.44	0.58	10.88	0.05	16.85	10.79	0.36	11.97	1.15	0.96	98.08

Sample #	SiO₂ %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	Cr <sub>2</sub> O <sub>3</sub> %	FeO %	MgO %	MnO %	CaO %	Na₂O %	K₂O %	Total
981002-7-1	42.28	0.66	13.71	0.02	19.14	7.67	0.37	11.56	1 35	0.66	97 47
981002-7-2	43.25	0.58	12.90	0.05	19.02	8.07	0.31	11.48	1.00	0.53	97.58
981002-7-3	42.65	0.62	13.45	0.00	19.08	7.95	0.34	11.65	1 43	0.54	97.00
981002-7-4	42.55	0.67	13.45	0.04	19.30	7.81	0.36	11 40	1.10	0.57	97 /9
981002-7-5	41.65	0.71	14.10	0.04	19.33	7.41	0.34	11 48	1.48	0.61	97.79
981002-7-6	42.10	0.62	13.64	0.00	19.23	7.65	0.37	11.59	1.40	0.59	97.22
981002-7-7	42.49	0.65	13.71	0.00	19.15	7.68	0.33	11.42	1 39	0.58	97 40
981002-7-8	42.83	0.61	13.08	0.00	18.81	7.98	0.36	11 48	1.39	0.55	97.40
981002-7-9	42.78	0.65	12.60	0.00	18.88	8.18	0.35	11.60	1 24	0.00	06.08
981002-7-10	41.91	0.64	13.83	0.04	18.97	7.61	0.40	11.00	1 47	0.61	90.90
981002-7-11	41.75	0.68	13.71	0.00	19.28	7.55	0.37	11.69	1.47	0.65	97.21
981002-7-12	42.06	0.65	13.77	0.03	19.18	7.60	0.38	11 72	1.39	0.62	97.17 97.49
981002-7-13	42.08	0.60	13.58	0.00	19.02	7.76	0.32	11 62	1.32	0.62	96.90
981002-7-14	41.53	0.64	14.00	0.02	19.03	7.55	0.38	11.71	1 42	0.57	96.89
981002-7-15	41.67	0.60	13.80	0.00	19.27	7.67	0.38	11.78	1.38	0.58	97.24
981002-7-16	41.99	0.67	13.56	0.01	19.28	7.79	0.38	11.66	1 41	0.54	07 <u>4</u> 0
981002-7-17	42.32	0.65	13.23	0.03	19.17	7.83	0.40	11.57	1.35	0.56	97.90
981002-7-18	42.26	0.63	13.27	0.02	19.11	7.89	0.34	11.62	1.37	0.57	97.17
981004-24-1	48.57	0.30	7.21	0.12	12.93	13.91	0.28	12 18	0.80	0.53	96.86
981004-24-2	48.37	0.27	7.25	0.01	13.16	13.84	0.26	12.10	0.00	0.00	<u> 96,00</u>
981004-24-3	48.45	0.31	7.01	0.00	13.07	13.98	0.28	12.59	0.70	0.00	96.92
981004-24-4	50.32	0.29	5.46	0.05	12.38	14.88	0.23	12.50	0.61	0.40	97 12
981004-24-5	49.22	0.30	6.65	0.02	12.83	14.25	0.28	12 49	0.67	0.46	97.12
981004-24-6	48.65	0.27	7.28	0.03	13.49	13.73	0.28	12.33	0.75	0.43	97.10
981004-24-7	47.30	0.42	8.69	0.03	13.88	12.96	0.28	12.06	1.03	0.72	97.30 97.41
981004-24-8	48.14	0.28	7.59	0.01	13.54	13.62	0.30	12.23	0.91	0.44	97 10
981004-24-9	49.56	0.30	6.30	0.04	12.60	14.52	0.28	12.30	0.70	0.44	97.09

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Sample #	SiO₂ %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	Cr <sub>2</sub> O <sub>3</sub> %	FeO %	MgO %	MnO %	CaO %	Na₂O %	K₂O %	Total
981004-24-10	50.40	0.25	5.14	0.01	11.79	15.29	0.28	12.38	0.60	030	96 49
981004-24-11	48.63	0.33	7.35	0.03	13 12	13.67	0.23	12.00	0.00	0.50	90.49
981004-24-12	49.29	0.26	6.21	0.05	12.63	14 40	0.20	12.17	0.70	0.52	90.07
981004-24-13	48.66	0.32	7.19	0.00	12.00	13.74	0.20	12.41	0.00	0.45	90.65
981004-24-14	50.52	0.25	5.54	0.06	12.28	15.02	0.22	12.33	0.62	0.00	90.91
981004-24-15	53.53	0.04	2.47	0.05	10.62	16.71	0.27	12.69	0.28	0.38	97.28 96.79
981009-5-1	43.68	0.61	10.63	0.01	17 82	10.38	0.34	11 37	1 56	0.50	07.06
981009-5-2	43.60	0.58	10.41	0.00	17 31	10.38	0.04	11.68	1.50	0.59	97.00
981009-5-3	42.99	0.73	11.21	0.00	18.13	9.93	0.39	11.00	1.52	0.59	90.00
981009-5-4	40.16	0.59	9,75	0.01	16.45	9.39	0.36	14 94	1.00	0.00	97.30
981009-5-5	44.78	0.65	9.91	0.00	17.49	10.82	0.00	11 45	1.72	0.01	90.19
981009-5-6	44.97	0.62	9.74	0.02	17.28	10.60	0.30	11.70	1.30	0.59	97.40
981009-5-7	43.77	0.63	10,72	0.02	17.77	10.32	0.00	11.70	1.54	0.57	97.20
981009-5-9	44.00	0.59	9.93	0.03	17.41	10.60	0.38	11.56	1.09	0.02	97.30
981009-5-10	43.75	0.58	10.05	0.00	17.67	10.58	0.38	11.50	1.40	0.51	90.01
981009-5-11	44.39	0.55	9.57	0.03	17.20	10.90	0.36	11.30	1.47	0.50	90.03
981009-5-12	43.47	0.63	10.44	0.00	17.78	10.25	0.40	11.36	1.43	0.61	96.38 96.38
981004-15-1	49.11	0.44	7.46	0.10	12.41	14.35	0.39	12 01	0.81	0.27	07 38
981004-15-2	46.73	0.52	9.48	0.16	13.31	13.05	0.36	11 91	0.97	0.27	97.50
981004-15-3	46.84	0.49	9.45	0.08	13.11	13.19	0.34	12 10	0.07	0.04	90.00
981004-15-4	46.57	0.53	9.20	0.18	13.18	13 18	0.34	12 18	0.00	0.04	90.90
981004-15-5	48.92	0.37	7.18	0.25	12.25	14.41	0.27	12.10	0.86	0.00	90.71
981004-15-6	47.24	0.46	9.43	0.00	13.06	13 23	0.31	11 94	1.06	0.23	97.07
981004-15-7	48.59	0.37	7.71	0.02	12.51	14.04	0.29	12 17	0.83	0.37	97.10
981004-15-8	<b>48.97</b>	0.33	7.21	0.04	12.11	14.60	0.29	12.17	0.00	0.02	90.00 90.00
981004-15-9	47.25	0.46	9.35	0.14	13.40	13.26	0.27	12.21	1.01	0.23	97.81

Sample #	SiO₂ %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	Cr₂O₃ %	FeO %	MgO %	MnO %	CaO %	Na₂O %	K₂O %	Total
981004-15-10	44.53	0.44	11.97	0 11	14.05	11 74	0.36	10.09	1.00		
981004-15-11	44.77	0.54	11.55	0.01	13.06	12.02	0.00	12.00	1.29	0.44	97.08
981004-15-12	45.01	0.52	11.67	0.04	14 13	11.02	0.31	10.40	1.26	0.43	96.84
981004-15-13	48.77	0.37	7.64	0.04	12.40	14.21	0.30	12.10	0.77	0.57 0.37	97.52 97.11
981005-5-1	47.70	0.40	7.97	0.07	11 87	14 64	0.22	12 40	0.02	0.04	~~~~
981005-5-2	47.54	0.35	7.84	0.06	11.07	14 53	0.22	12.40	0.93	0.64	96.87
981005-5-3	48.04	0.38	7.70	0.00	11 93	14.00	0.20	12.17	0.99	0.66	96.42
981005-5-4	46.92	0.44	8.19	0.13	12.60	14.07	0.27	12.20	0.93	0.60	96.90
981005-5-5	47.20	0.45	8.39	0.08	12.00	14.13	0.20	12.43	1.00	0.61	96.68
981005-5-6	48.31	0.36	7.62	0.01	12.00	14.80	0.20	12.34	1.08	0.63	96.99
981005-5-7	47.90	0.37	7.65	0.02	12.00	14.51	0.20	12.21	0.93	0.50	97.08
981005-5-8	47.72	0.36	7.92	0.05	12.30	14.28	0.20	12.30	0.91	0.68	96.92
981005-5-9	45.91	0.48	9.20	0.02	12.00	13 54	0.20	12.20	0.90	0.69	96.73
981005-5-10	47.14	0.43	8.32	0.01	12.47	13.98	0.25	12.19	1.00	0.87 0.62	96.48 96.46
981005-15-1	47.00	0.50	8.39	0.05	16 44	10.85	0.42	11 95	0.00	0.40	
981005-15-2	47.43	0.43	7.81	0.04	16 18	11 12	0.42	11.00	0.90	0.19	96.64
981005-15-3	47.59	0.48	7.90	0.03	16.10	11.09	0.41	11.00	0.07	0.15	96.33
981005-15-4	48.45	0.45	7.51	0.02	15.77	11.38	0.40	11.00	0.93	0.10	96.69
981005-15-5	48.04	0.51	8.03	0.08	16 25	11.00	0.00	11 75	0.77	0.20	96.82
981005-15-6	48.30	0.41	7.46	0.05	16.32	11.20	0.40	11.70	0.00	0.21	97.47
981005-15-7	45.81	0.59	10.23	0.05	16.80	9.92	0.40	10.00	0.82	0.32	97.44
981005-15-8	48.25	0.28	7.22	0.25	16.00	11 44	0.40	12.03	0.99	0.24	97.11
981005-15-9	44.59	0.58	10.88	0.18	17 77	9.02	0.39	12.14	0.59	0.26	96.87
981005-15-10	46.22	0.44	9.84	0.03	16 14	10 33	0.39	10.00	1.10	0.3/	96.93
981005-15-11	45.83	0.60	9.86	0.02	16.75	10.23	0.30	11.83	1.11	0.37	96.90 96.97

Sample #	SiO₂ %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	Cr <sub>2</sub> O <sub>3</sub> %	FeO %	MgO %	MnO %	CaO %	Na₂O %	K₂O %	Total
981004-21-1	49.71	0.28	5.30	0.03	14.28	13 81	0.30	11 97	0.80	0.49	07.44
981004-21-2	50.69	0.19	4,55	0.04	13.74	14 68	0.32	11.07	0.09	0.40	97.11
981004-21-3	48.95	0.26	5.97	0.09	14 70	13.66	0.02	12.06	0.73	0.30	97.14
981004-21-4	49.03	0.53	5.67	0.03	14 66	13.69	0.35	11.00	0.01	0.55	97.34
981004-21-5	48.28	0.33	6.14	0.05	14.95	13 25	0.34	11.75	1.02	0.44	97.10
981004-21-6	47.99	0.31	6,40	0.00	15.21	13.32	0.35	11 77	1.03	0.50	96.80
981004-21-7	47.83	0.34	6,52	0.02	15.28	12.97	0.34	11 00	1.01	0.00	97.07
981004-21-8	48.33	0.34	6.29	0.02	15.33	13 15	0.33	11.35	1.02	0.64	97.02
981004-21-9	47.54	0.40	7.03	0.01	15.82	12 71	0.35	11 97	1.05	0.09	97.33
981004-21-10	47.96	0.33	6.73	0.07	15.29	13.01	0.34	11.88	1.00	0.00	97.07
981004-21-11	47.49	0.34	6.88	0.10	15.38	12.90	0.04	11.00	1.09	0.00	97.31
981004-21-12	48.31	0.36	6.18	0.05	14.86	13.27	0.34	11.84	1.03	0.73	97.18 96.90
981005-9-1	50.26	0.24	4.67	0.10	13 19	14 82	0.27	10 10	0.07	0.55	07.40
981005-9-2	50.32	0.25	4.78	0.03	13.03	15 13	0.27	14 00	0.07	0.55	97.12
981005-9-3	50.55	0.23	4.44	0.08	12.89	15.15	0.31	11.02	1.12	0.51	97.33
981005-9-4	50.88	0.23	4.26	0.06	12.00	15.00	0.20	11.00	1.14	0.43	97.30
981005-9-5	49.57	0.32	5.37	0.10	13.99	14 51	0.20	11.92	1.02	0.42	97.56
981005-9-6	50.83	0.26	4.10	0.09	12.83	15.23	0.20	12.05	0.90	0.01	97.76
981005-9-7	50.09	0.30	4.75	0.00	13 16	15.20	0.20	12.00	0.09	0.43	97.02
981005-9-8	50.05	0.24	4.85	0.02	13.02	15.00	0.29	11.75	1.10	0.55	97.12
981005-9-9	50.97	0.21	4.34	0.01	12 78	15.00	0.02	11.00	1.15	0.53	97.13
981005-9-10	50.87	0.21	4.13	0.26	12.65	15.26	0.23	11.50	1.00	0.43	97.40
981005-9-11	50.62	0.24	4.43	0.10	12.88	15.20	0.27	11.79	1.09	0.49	97.12
981005-9-12	50.17	0.30	4.70	0.11	12.00	14 91	0.20	11.//	1.13	0.42	97.22
981005-9-13	51.05	0.25	4.09	0.11	12.60	15 73	0.00	11.07	1.12	0.51	96.97
981005-9-14	50.91	0.25	4.33	0.02	13.03	15.75	0.23	11.00		0.44	97.54
981005-9-15	49.81	0.35	5.17	0.12	13.48	14.71	0.24	12.21	0.90	0.47 0.55	97.47 97.50

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Sample #	SiO₂ %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	Cr₂O₃ %	FeO %	MgO %	MnO %	CaO %	Na₂O %	K₂O %	Total
981005-9-16	50.96	0.28	4.25	0.11	12.88	15.46	0.26	12.14	0.97	0.44	97.78
981005-9-17	50.29	0.26	4.50	0.05	13.00	15.31	0.26	11.87	1.00	0.48	97.02
981005-9-18	50.56	0.23	4.15	0.02	12.96	15.36	0.24	12.12	0.91	0.44	97.05
981005-9-19	50.55	0.29	4.46	0.11	13.11	15.15	0.26	11.96	1.03	0.49	97 43
981005-9-20	51.17	0.21	3.85	0.07	12.85	15.53	0.26	12.10	0.90	0.39	97.37
981005-7-1	52.84	0.14	3.07	0.08	10.78	16.71	0.24	12.53	0 49	0 24	97 17
981005-7-2	52.96	0.19	2.94	0.10	10.63	16.72	0.28	12.74	0.48	0.28	97.37
981005-7-3	53.08	0.13	2.81	0.09	10.70	16.73	0.29	12.59	0.51	0.28	97.25
981005-7-4	52.98	0.14	3.31	0.07	10.77	16.64	0.31	12.65	0.55	0.29	97.81
981005-7-5	53.41	0.16	2.72	0.05	10.55	16.78	0.25	12.67	0.43	0.23	97.30
981005-7-7	53.53	0.14	2.68	0.09	10.41	16.96	0.27	12.39	0.47	0.25	97.23
981005-7-8	53.52	0.13	2.77	0.01	10.64	17.03	0.28	12.48	0.46	0.27	97 60
981005-7-9	53.40	0.11	2.53	0.05	10.58	16.81	0.29	12.40	0.44	0.23	96.87
981005-7-10	54.16	0.05	1,87	0.05	10.38	17.55	0.27	12.65	0.38	0.15	97.52
981005-7-11	54.02	0.16	2.54	0.10	10.53	16.87	0.28	12.62	0.35	0.23	97.75
981005-7-12	53.60	0.16	2.60	0.15	10.62	17.06	0.26	12.57	0.38	0.23	97.69
981005-7-13	53.52	0.11	2.49	0.04	10.33	17.06	0.27	12.48	0.50	0.22	97 10
981005-7-14	53.06	0.12	3.08	0.07	10.65	16.83	0.34	12.48	0.59	0.28	97.50
981005-7-15	54.69	0.01	1.48	0.01	10.07	17.39	0.24	13.16	0.17	0.07	97.31
981005-7-16	53.65	0.08	2.35	0.14	10.62	17.20	0.30	12.56	0.43	0.23	97.62
981004-10-1	48.72	0.30	7.75	0.01	11.12	15.47	0.26	12.24	0.90	0.15	96 96
981004-10-2	46.92	0.41	9.11	0.03	11.83	14.33	0.24	12.25	1.14	0.20	96.47
981004-10-3	49.17	0.26	7.44	0.00	10.79	15.55	0.27	12.32	0.92	0.13	96 85
981004-10-4	48.01	0.26	8.69	0.02	11.46	14.83	0.28	12.26	1.13	0.09	97.04
981004-10-5	46.88	0.46	9.52	0.00	12.05	14.19	0.30	12.13	1.12	0.26	96.94
981004-10-6	46.57	0.39	9.56	0.03	12.03	14.06	0.27	12.29	1.09	0.24	96.57

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Sample #	SiO₂ %	TiO₂ %	Al₂O₃ %	Cr <sub>2</sub> O <sub>3</sub> %	FeO %	MgO %	MnO %	CaO %	Na₂O %	K₂O %	Total
981004-10-7	48.82	0.34	7.35	0.06	10.69	15.65	0.26	12.43	0.83	0.12	96.54
981004-10-8	48.16	0.44	8.38	0.04	11.35	15.04	0.27	12.22	0.99	0.16	97.06
981004-10-9	46.22	0.48	9.65	0.02	12.22	14.03	0.24	12.17	1.20	0.29	96.51
981004-10-10	48.92	0.32	7.83	0.01	11.03	15.13	0.22	12.24	0.94	0.17	96.81
981004-10-11	50.23	0.42	6,55	0.07	10.48	16.12	0.27	12.41	0.75	0.08	97.38
981004-10-12	49.72	0.33	7.06	0.05	10.54	15.86	0.23	12.36	0.91	0.14	97.22
981004-10-13	50.67	0.32	5.81	0.03	9.95	16.34	0.24	12.41	0.78	0.09	96.70
981004-10-14	51.50	0.18	4,87	0.00	9.59	17.09	0.27	12.34	0.61	0.07	96.58
981004-10-15	49.33	0.39	7.29	0.04	11.02	15.62	0.26	12.44	0.85	0.13	97.40
981004-10-16	48.15	0.45	8.05	0.05	11.28	14.99	0.27	12.26	0.98	0.17	96.71
981004-10-17	47.94	0.44	8.08	0.00	11.32	15.05	0.25	12.33	0.96	0.20	96.56
981004-10-18	48.48	0.44	7.94	0.01	11.30	15.06	0.21	12.31	0.95	0.17	96.89
981004-10-19	47.55	0.47	8.60	0.09	11.72	14.57	0.25	12.25	1.03	0.23	96.77
981009-4-1	41.48	0.64	13.39	0.00	19.09	8.22	0.44	11.78	1.27	0.69	97.08
981009-4-2	41.38	0.44	14.40	0.02	19.08	7.92	0.52	11.79	1.38	0.49	97 52
981009-4-3	41.52	0.47	14.48	0.01	19.09	7.85	0.49	11.91	1 35	0.53	97 71
981009-4-4	41.16	0.61	14.20	0.02	19.41	7.89	0.50	11.92	1.40	0.57	97 71
981009-4-5	41.75	0.66	13.15	0.01	18.68	8.32	0.46	11.78	1.29	0.68	96.86
981009-4-6	41.69	0.58	13.45	0.01	18.94	8.17	0.47	11.84	1.28	0.75	97.18
981009-4-7	43.43	0.53	11.84	0.01	18.10	9.25	0.44	11.93	1.14	0.57	97.25
981009-4-8	43.04	0.57	12.13	0.02	18.55	9.07	0.46	11.71	1.23	0.62	97.46
981009-4-9	42.55	0.60	12.80	0.01	19.12	8.41	0.50	11.77	1.28	0.59	97.68
981009-4-10	41.60	0.55	13.56	0.03	19.11	8.21	0.49	11.82	1.29	0.60	97 35
981009-4-11	41.32	0.57	14.11	0.00	19.58	7.86	0.55	11.68	1.37	0.54	97.68
981009-4-12	42.47	0.60	12.51	0.01	18.83	8.60	0.46	11.85	1.23	0.65	97.21

981009-4-13

981009-4-14

981009-4-15

42.03

42.90

41.60

0.56

0.53

0.68

13.31

12.37

13.41

0.02

0.00

0.01

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19.27

18.48

18.99

8.42

8.91

8.18

0.48

0.45

0.47

11.80

11.91

11.90

1.24

1.18

1.31

0.67

0.63

0.74

97.82

97.40

97.36

Sample #	SiO₂ %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	Сг <sub>2</sub> О <sub>3</sub> %	FeO %	MgO %	MnO %	CaO %	Na₂O %	K₂O %	Total
971007-1-1	45.17	0.39	10.44	0.00	20 58	7 70	0 25	11 92	0.96	0.05	07 54
971007-1-2	45.76	0.35	9.76	0.01	20.24	8.28	0.20	12 10	0.00	0.00	97.54
971007-1-3	46.19	0.40	9.25	0.00	20.46	8 25	0.20	11 97	0.82	0.00	07 70
971007-1-4	45.33	0.50	10.68	0.01	19.92	7.94	0.26	11.96	0.02	0.02	97.79
971007-1-6	45.20	0.47	10.82	0.04	19.65	7.96	0.29	11.00	0.04	0.07	97 44
971007-1-7	44.88	0.44	12.14	0.03	18.79	8.04	0.32	11.00	0.07	0.00	07 50
971007-1-8	45.72	0.42	10.14	0.00	19.12	8.63	0.28	11.83	0.95	0.00	97.00
971007-1-9	45.27	0.53	11.01	0.01	19.06	8.25	0.28	11.68	0.98	0.06	97.20
971007-1-10	44.71	0.48	11.59	0.03	19.50	7.91	0.29	11.60	1.01	0.07	97.30
NGS-51-205.5-1	40.54	0.39	16.14	0.00	21.14	5.82	0.12	11 28	1.32	0.48	97 24
NGS-51-205.5-2	40.77	0.43	15.62	0.15	21.26	5.91	0.13	11.41	1.31	0.40	97.36
NGS-51-205.5-3	40.44	0.41	15.84	0.31	21.34	5.92	0.13	11.24	1.30	0.43	97.36
NGS-51-205.5-5	41.06	0.34	15.86	0.28	20.79	6.13	0.12	11.47	1.34	0.44	97 84
NGS-51-205.5-6	40.33	0.38	16.68	0.00	20.37	6.01	0.08	10.95	1.48	0.52	96 79
NGS-51-205.5-7	40.46	0.41	16.81	0.01	20.37	6.13	0.10	11.01	1.53	0.52	97.34
NGS-51-205.5-8	41.01	0.31	15.99	0.02	20.42	6.32	0.09	10.94	1.50	0.44	97.08
NGS-51-205.5-9	40.34	0.46	16.32	0.00	20.40	6.10	0.10	11.00	1.53	0.48	96.78
NGS-51-205.5-10	40.34	0.33	17.17	0.00	20.25	6.00	0.08	10.89	1.55	0.52	97.13
T95-9-402.7-1	41.46	0.55	13.75	0.03	20.41	7.19	0.07	11.48	1.37	0.68	96 98
T95-9-402.7-2	41.52	0.56	13.65	0.09	20.61	7.00	0.06	11.29	1.37	0.72	96.89
T95-9-402.7-3	41.93	0.64	13.55	0.03	20.51	7.37	0.06	11.47	1.37	0.65	97 57
T95-9-402.7-4	42.15	0.52	13.51	0.03	19.84	7.46	0.07	11.59	1.32	0.68	97.20
T95-9-402.7-5	41.94	0.59	13.56	0.05	20.35	7.35	0.09	11.37	1.29	0.63	97.24
T95-9-402.7-6	41.05	0.58	13.99	0.03	20.65	6.89	0.08	11.37	1.48	0.71	96 84
T95-9-402.7-7	41.53	0.62	13.82	0.09	20.22	7.13	0.06	11.45	1.34	0.71	96.98
T95-9-402.7-8	41.42	0.59	13.80	0.07	20.71	7.15	0.08	11.39	1.41	0.67	97.32
T95-9-402.7-9	41.59	0.67	13.86	0.07	20.44	7.18	0.06	11.57	1.41	0.73	97.66

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Sample #	SiO₂ %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	Cr <sub>2</sub> O <sub>3</sub> %	FeO %	MgO %	MnO %	CaO %	Na₂O %	K₂O %	Total
T95-9-402.7-10	41.46	0.47	13.73	0.03	20.63	7 25	0 09	11 /8	1 27	0.64	07.45
T95-9-402.7-11	41.36	0.37	13.94	0.09	20.14	7.20	0.08	11.33	1.34	0.65	97.15 96.51
970704-7-1	51.00	0.25	5 45	0.05	12 20	14 99	0.27	40.54	0.47		
970704-7-2	50.69	0.25	5.86	0.00	12.20	14.00	0.37	12.51	0.47	0.20	97.43
970704-7-3	52.58	0.18	3.66	0.01	14.15	14.00	0.40	12.46	0.43	0.22	97.32
970704-7-4	52 72	0.10	3,80	0.00	11.20	10.90	0.34	12.35	0.28	0.13	96.78
970704-7-5	53 12	0.14	3,02	0.02	11.10	16.24	0.35	12.56	0.29	0.12	97.49
970704-7-6	52 92	0.10	3.03	0.00	11.55	16.16	0.36	12.49	0.23	0.10	97.85
97070 <i>A</i> _7.7	02.03	0.15	3.60	0.04	11.47	16.12	0.32	12.56	0.26	0.12	97.47
970704 7 0	49.87	0.06	9.00	0.02	8.74	11.99	0.21	16.50	0.09	0.04	96.54
070704 7 0	52.85	0.15	3.44	0.01	11.32	16.15	0.31	12.54	0.20	0.10	97.11
9/0/04-/-9	52.76	0.17	3.13	0.05	11.39	16.39	0.36	12.46	0.21	0.10	97 04
9/0/04-/-10	50.74	0.29	6.09	0.01	12.15	15.03	0.37	12.46	0.48	0.20	07.04
970704-7-11	50.50	0.32	6.54	0.00	12.21	14.70	0.37	12.35	0.48	0.20	07.71
970704-7-12	50.43	0.31	6.32	0.00	12.03	14 70	0.35	12.00	0.40	0.24	97.71
970704-7-13	52.03	0.16	4.28	0.04	11 45	15.80	0.00	12.10	0.40	0.21	97.00
970704-7-15	50.30	0.28	6 30	0.00	11 59	15.00	0.00	12.34	0.31	0.16	96.93
970704-7-16	47.95	0.44	9.08	0.00	12 22	12.01	0.37	12.04	0.58	0.23	96.74
970704-7-17	48 65	0.34	7.88	0.00	12.02	13.45	0.37	12.07	0.75	0.37	96.82
970704-7-19	46.08	0.42	0.70	0.01	12.00	14.23	0.38	12.10	0.67	0.37	96.68
	-0.30	0.43	9.19	0.00	12.60	13.23	0.36	12.05	0.86	0.38	96.69

Amphibole 13

Sample #	SiO₂ %	TiO₂ %	Al <sub>2</sub> O <sub>3</sub> %	Cr₂O₃ %	FeO %	MgO %	MnO %	CaO %	Na₂O %	K₂O %	Total
981004-26-1	48.23	0.43	7.57	0.07	14.96	12 67	0.39	12.00	0.67	0.49	07.54
981004-26-2	45.44	0.55	10.12	0.22	15 87	11.06	0.00	11 06	0.07	0.40	97.51
981004-26-3	47.77	0.42	7.86	0.05	15 11	12 20	0.00	11.00	0.90	0.75	97.36
981004-26-4	45.86	0.52	9.36	0.03	15 75	11 37	0.40	12.04	0.76	0.51	97.22
981004-26-5	48.57	0.34	6.90	0.09	14 32	12 91	0.41	12.04	0.95	0.67	97.01
981004-26-6	45.62	0.49	9.37	0.08	15.87	11 30	0.03	12.22	0.02	0.42	96.86
981004-26-7	48.99	0.33	6.83	0.00	14 60	10.00	0.40	12.21	0.81	0.66	96.84
981004-26-8	44.21	0.50	11 64	0.04	16.51	12.00	0.40	12.03	0.64	0.42	97.28
981004-26-9	48.99	0.40	6.94	0.02	14.80	10.05	0.40	11.93	1.19	0.63	97.14
981004-26-10	46.24	0.53	9.17	0.04	15 60	12.75	0.39	12.00	0.70	0.41	97.50
981004-26-11	46.11	0.49	9.24	0.00	15.50	11.00	0.38	12.06	0.93	0.64	97.21
981004-26-12	47 45	0.40	7.60	0.05	10.01	11.40	0.39	12.08	0.83	0.62	96.76
981004-26-13	44 15	0.50	11 66	0.07	14.77	12.35	0.41	12.14	0.77	0.51	96.50
981004-26-14	49.05	0.00	6.50	0.10	16.73	9.91	0.43	12.00	0.96	0.73	97.25
981004-26-15	18 Q1 ·	0.30	0.52	0.13	14.35	13.24	0.39	12.18	0.59	0.40	97.21
981004-26-16	40.51	0.37	0,00	0.09	14.16	13.02	0.44	12.05	0.67	0.38	96.64
981004-26-17	40.44	0.37	/.49	0.08	14.61	12.73	0.48	12.17	0.70	0.43	97.61
981004-26-18	40.19	0.57	10.07	0.07	15.64	11.10	0.41	12.03	0.88	0.74	96.81
001004-20-10	40.63	0.49	9,96	0.11	15.54	11.23	0.41	12.17	0.88	0.69	97.13

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### Hemlo Plagioclase Probe Data

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 20 nA; 20 s peak counts; 5 um beam.

Total Fe as FeO. Lower detection limits at 2SD are 0.01-0.02 wt %.

Orthoclase-, albite, spessartine, garnet, and diopside-based standards for all major elements.

Plagioclase analyses for amphibole-plagioclase geothermometry.

Sample	SiO2	AI2O3	TiO2	FeO	MgO	MnO	CaO	BaO	Na2O	K2O	Total
·	%	%	%	%	%	%	%	%	%	%	
971007_7-1	60.00	25.62	0.00	0.07	0.00	0.02	7.02	0.00	7.76	0.15	100.64
971007_7-2	61.24	24.60	0.00	0.10	0.01	0.00	5.94	0.00	8.46	0.14	100.49
971007_7-7	60.19	24.76	0.00	0.28	0.01	0.00	6.32	0.00	8.03	0.10	99.69
971007_7-8	59.13	25.54	0.01	0.15	0.00	0.00	7.13	0.00	7.56	0.13	99.65
971007_7-20	58.90	25.72	0.03	0.19	0.01	0.00	7.46	0.00	7.34	0.10	99.76
971007_7-21	58.78	25.69	0.03	0.17	0.00	0.01	7.52	0.00	7.53	0.11	99.88
971007_7-22	58.83	25.67	0.00	0.13	0.00	0.00	7.48	0.00	7.44	0.14	99.68
971007_7-23	59.15	25.74	0.01	0.14	0.01	0.00	7.24	0,00	7.49	0.14	99.93
971007_7-24	64.07	22.27	0.00	0.09	0.00	0.00	3.33	0.00	9.93	0.08	99.82
971007_7-25	59.03	25.54	0.04	0.14	0.00	0.00	7.24	0.00	7.47	0.10	99.57
971007_7-26	59.28	25.49	0.02	0.18	0.00	0.00	7.13	0.00	7.62	0.13	99.85
971007_7-27	59.62	25.34	0.00	0.14	0.00	0.00	6.97	0.00	7.71	0.12	99.94
971007_7-28	59.72	25.23	0.00	0.12	0.00	0.00	6.96	0.00	7.60	0.14	99.81
971007_7-29	61.42	24.38	0.04	0.20	0.01	0.00	5.68	0.00	8.47	0.09	100.30
971007_7-30	62.39	23.38	0.02	0.16	0.00	0.03	4.73	0.00	8.82	0.18	99.76
971007_7-31	60.77	24.54	0.02	0.10	0.00	0.00	6.14	0.00	8.23	0.16	99.97
971007_7-32	59.68	25.12	0.01	0.10	0.00	0.03	7.00	0.00	7.5 <del>9</del>	0.20	99.72
971007_7-33	59.66	25.28	0.02	0.08	0.00	0.00	6.87	0.00	7.63	0.20	99.77
971007_7-34	59.51	25.34	0.01	0.10	0.01	0.02	6.98	0.00	7.54	0.15	<del>9</del> 9.68
971007_7-35	59.54	25.06	0.00	0.17	0.01	0.01	6.97	0.00	7.69	0.11	99.56
971007_7-36	60.13	24.91	0.00	0.10	0.00	0.00	6.57	0.00	7.88	0.11	99.74
971007_7-37	61.96	23.79	0,00	0.06	0.00	0.00	5.14	0.00	8.63	0.15	99.73
971007_7-38	61.31	23.96	0.00	0.07	0.00	0.00	5.51	0.00	8.56	0.16	99.65
971007_7-39	59.37	25.19	0.00	0.09	0.01	0.00	6.92	0.00	7.62	0.13	99.32
971007_7-40	59.55	25.19	0.00	0.14	0.00	0.00	6.91	0.00	7.78	0.11	99.69

Plagioclase (mafic) 1

Sample	<b>SiO2</b> %	AI2O3 %	<b>TiO2</b> %	FeO %	MgO %	MnO %	CaO %	BaO %	Na2O %	K2O %	Total
971008_1-9	60.96	24.01	0.00	0.17	0.00	0.00	5.70	0.00	8.28	0 15	99.28
971008_1-10	63.66	22.26	0.02	0.12	0.00	0.00	3.74	0.00	9.60	0.03	99.45
971008_1-11	63.52	23.28	0.03	0.31	0.11	0.04	1.53	0.00	8.81	2.22	99.86
971008_1-12	59.46	25.15	0.02	0.13	0.00	0.01	7.03	0.00	7.61	0 11	99.52
971008_1-13	65.26	21.60	0.01	0.16	0.00	0.00	2.70	0.00	10.17	0.04	99.95
971008_1-14	60.14	24.62	0.02	0.10	0.01	0.02	6.26	0.00	8.01	0.12	99.35
971008_1-15	61.02	23.84	0.00	0.11	0.01	0.02	5.68	0.00	8.44	0.13	99.27
971008_1-16	65.79	21.29	0.04	0.05	0.00	0.00	2.27	0.00	10.62	0.09	100.17
971008_1-17	68.91	19.96	0.02	0.17	0.00	0.00	0.33	0.00	11.58	0.05	101.05
971009_9-9	61.89	23.58	0.00	0.28	0.00	0.01	4.98	0.00	8.80	0.11	99.65
971009_9-10	62.55	22.95	0.00	0.15	0.00	0.01	4.49	0.00	9.19	0.08	99.41
971009_9-11	62.12	23.26	0.01	0.19	0.00	0.00	4.81	0.00	8.81	0.12	99.35
971009_9-12	59.65	24.68	0.02	1.13	0.35	0.01	0.90	0.00	6.79	4.54	98.09
971009_9-13	60.57	24.45	0.00	0.22	0.00	0.02	5.96	0.00	8.31	0.13	99.65
971009_9-14	60.29	24.38	0.00	0.16	0.00	0.00	6.26	0.00	8.12	0.10	99.31
971009_9-15	61.44	23.57	0,00	0.17	0.01	0.01	5.20	0.00	8.40	0.12	98.91
971009_9-20	68.45	19.14	0.00	0.13	0.01	0.00	0.05	0.00	11.86	0.04	99.71
971009_9-21	67.15	19.92	0.00	0.15	0.00	0.00	0.86	0.00	11.08	0.11	99.28
971009_9-22	68.82	19.36	0.00	0.05	0.00	0.00	0.03	0.00	11.80	0.04	100.10
T226-28.8-1	64.95	22.48	0.00	0.19	0.00	0.01	3.35	0.00	9.59	0.08	100.65
T226-28.8-2	65.69	22.27	0.01	0.17	0.00	0.03	3.05	0.00	9.89	0.09	101.20
T226-28.8-3	63.95	19.41	0.02	0.12	0.00	0.00	0.88	0.00	4.38	9.96	98.73
T226-28.8-12	64.56	22.07	0.00	0.23	0.01	0.00	3.26	0.00	9.62	0.07	99.86
T226-28.8-13	64.23	22.05	0.00	0.30	0.00	0.00	3.14	0.00	9.74	0.06	99.53
T226-28.8-14	64.98	22.15	0.00	0.32	0.01	0.01	3.19	0.00	9.85	0.05	100.57
T226-28.8-15	63.94	22.01	0.00	0.16	0.00	0.00	3.23	0.00	9.71	0.06	99.13
T226-28.8-16	64.52	21.86	0.03	0.26	0.00	0.02	3.09	0.00	9.98	0.06	99.87
T226-28.8-17	64.29	21.94	0.01	0.17	0.00	0.00	3.37	0.00	9.71	0.07	99.59

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Sample	SiO2	AI2O3	TiO2	FeO	MgO	MnO	CaO	BaO	Na2O	K2O	Total
	%	%	%	%	%	%	%	%	%	%	
970709-1-1	60.90	24.60	0.01	0.24	0.00	0.00	5.76	0.00	8.28	0.05	99.85
970709-1-2	60.78	24.55	0.02	0.05	0.01	0.00	5.92	0.00	8.27	0.05	99.64
970709-1-3	61.74	23.83	0.06	0.28	0.01	0.00	5.06	0.00	8.94	0.04	99.99
970709-1-4	60.60	24.75	0.02	0.20	0.00	0.00	6.05	0.00	8.24	0.05	99.93
970709-1-5	61.89	24.35	0.00	0.11	0.01	0.01	5.39	0.00	8.69	0.05	100.55
970709-1-7	62.14	24.36	0.01	0.23	0.00	0.00	5.59	0.00	8.67	0.05	101.05
970709-1-8	61.61	24.65	0.00	0.14	0.02	0.00	5.86	0.00	8.39	0.06	100.76
970709-1-9	60.20	24.57	0.03	0.42	0.09	0.00	6.25	0.00	8.07	0.07	99.68
970709-1-10	60.38	24.32	0.00	0.25	0.00	0.00	5.89	0.00	8.14	0.05	99.05
970709-1-12	59.05	25.83	0.02	0.27	0.00	0.00	7.36	0.00	7.47	0.06	100.11
970709-1-15	60.94	24.11	0.01	0.19	0.00	0.01	5.56	0.00	8.51	0.06	99.41
970709-1-16	59.99	25.01	0.00	0.23	0.01	0.02	6.44	0.00	8.11	0.04	99.83
970709-1-17	60.03	24.58	0.00	0.14	0.01	0.01	5.92	0.00	8.31	0.06	99.05
970709-1-18	61.15	24.45	0.00	0.30	0.00	0.02	5.78	0.00	8.25	0.05	100.01
970709-1-19	60.80	24.68	0.05	0.23	0.00	0.00	5.83	0.00	8.41	0.06	100.08
970709-1-20	61.59	23.99	0.00	0.14	0.00	0.00	5.26	0.00	8.59	0.06	99.65
970709-1-21	62.44	23.72	0.00	0.13	0.00	0.00	4.94	0.00	8.82	0.05	100.11
970709-12-1	62.60	23.04	0.03	0.08	0.01	0.00	3.94	0.00	9.27	0.18	99.15
970709-12-2	63.02	22.88	0.00	0.08	0.01	0.02	4.21	0.00	9.15	0.19	99.57
970709-12-3	62.96	23.24	0.01	0.10	0.00	0.00	4.16	0.00	9.18	0.19	99.86
970709-12-4	62.63	23.15	0.00	0.07	0.00	0.00	4.22	0.00	9.01	0.21	99.29
970709-12-8	63.24	23.05	0.01	0.21	0.00	0.00	3.93	0.00	9.42	0.10	99.97
970709-12-9	63.97	22.41	0.00	0.08	0.01	0.00	3.30	0.00	9.72	0.21	99.73
970709-12-10	64.06	22.60	0.01	0.08	0.00	0.01	3.50	0.00	9.62	0.25	100.15
970709-12-11	62.67	23.17	0.00	0.05	0.00	0.00	4.14	0.00	9.20	0.21	99.45
970709-12-12	62.88	23.06	0.02	0.18	0.00	0.00	4.11	0.00	9.17	0.14	99.55
970709-12-13	63.04	23.03	0.00	0.09	0.00	0.00	4.07	0.00	9.32	0.20	99.75
970709-12-14	62.84	23.05	0.00	0.10	0.00	0.00	4.28	0.00	9.04	0.17	99.47
970709-12-15	62.70	23.08	0.00	0.07	0.00	0.00	4.19	0.00	9.11	0.20	99.40
970709-12-16	62.83	23.86	0.00	0.12	0.00	0.01	2.20	0.00	8.77	1.76	99.61
970709-12-17	63.23	23.21	0.00	0.07	0.00	0.00	4.29	0.00	9.27	0.20	100.27
970709-12-18	62.61	23.17	0.00	0.09	0.01	0.00	4.13	0.00	9.18	0.15	99.38

Plagioclase (mafic) 3
Sample	SiO2	Al2O3	TiO2	FeO	MgO	MnO	CaO	BaO	Na2O	K2O	Total
	%	%	%	%	%	%	%	%	%	%	
970709-11A-1	63.18	22.80	0.00	0.10	0.00	0.02	4.05	0.00	9.22	0.15	99.51
970709-11A-2	63.95	22.67	0.00	0.09	0.00	0.00	3.68	0.00	9.45	0,14	99.97
970709-11A-3	62.23	22.65	0.00	0.11	0.00	0.00	4.12	0.00	9.20	0.17	<del>9</del> 8.52
970709-11A-4	64.18	22.89	0.00	0.13	0.00	0.00	4.02	0.00	9.27	0.14	100.65
970709-11A-5	62.63	22.96	0.00	0.15	0.00	0.01	4.08	0.00	9.24	0.16	99.23
970709-11A-6	63.81	22.09	0.00	0.10	0.00	0.00	3.12	0.00	9.78	0.14	99.05
970709-11A-7	64.73	22.77	0.00	0.13	0.00	0.00	4.12	0.00	9.39	0.14	101.28
970709-11A-9	64.52	22.26	0.03	0.17	0.00	0.01	3.04	0.00	9.81	0.14	100.01
970709-11A-10	62.98	23.41	0.00	0.20	0.00	0.00	4.33	0.00	9.02	0.16	100.13
970709-11A-11	63.28	22.91	0.00	0.14	0.01	0.00	3.55	0.00	9.51	0.22	99.60
981005-6-1	59.78	24.96	0.00	0.13	0.00	0.01	6.68	0.00	7.73	0.08	99.36
981005-6-2	59.71	25.09	0.03	0.16	0.00	0.00	7.07	0.00	7.74	0.09	99.91
981005-6-3	60.49	24.52	0.00	0.08	0.00	0.00	6.15	0.00	8.11	0.09	99.45
981005-6-4	58.52	25.64	0.01	0.20	0.00	0.00	7.64	0.00	7.19	0.06	99.27
981005-6-5	60.28	24.97	0.00	0.21	0.00	0.02	6.57	0.00	7.80	0.08	99.97
981005-6-6	59.34	25.51	0.03	0.22	0.00	0.02	7.09	0.00	7.50	0.09	99.84
981005-6-7	59.44	25.34	0.00	0.17	0.00	0.00	6.93	0.00	7.65	0.11	99.69
981005-6-8	58.98	25.34	0.00	0.14	0.01	0.00	7.15	0.00	7.61	0.10	99.34
981005-6-9	58.55	25.88	0.00	0.29	0.00	0.01	7.73	0.00	7.23	0.10	99.79
981005-6-10	59.09	25.85	0.02	0.19	0.01	0.01	7.44	0.00	7.43	0.10	100.18
981005-6-11	60.13	25.07	0.02	0.19	0.00	0.03	6.72	0.00	7.94	0.08	100.17
981005-6-12	58.30	24.93	0.03	1.30	0,88	0.05	6.47	0.00	7.39	0.14	99.55
981005-6-13	58.28	26.18	0.00	0.27	0.00	0.00	8.05	0.00	7.19	0.10	100.12
981002-7-1	56.96	27.00	0.01	0.27	0.01	0.00	9.08	0.00	6.50	0.04	99.86
981002-7-2	60.43	24.78	0.03	0.44	0.00	0.00	6.20	0.00	8.13	0.05	100.06
981002-7-3	58.34	25.85	0.00	0.23	0.00	0.00	8.00	0.00	7.11	0.05	99.58
981002-7-4	59.69	25.27	0.00	0.35	0.01	0.00	6.84	0.00	7.82	0.04	100.06
981002-7-5	58.80	25.79	0.01	0.16	0.00	0.01	7.54	0.00	7.35	0.02	99.68
981002-7-6	59.50	25.63	0.02	0.15	0.00	0.00	7.20	0.00	7.57	0.03	100.10
981002-7-7	59.60	25.31	0.01	0.27	0.00	0.00	7.10	0.00	7.75	0.05	100.10
981002-7-8	58.90	25.87	0.00	0.22	0.00	0.04	7.77	0.00	7.34	0.05	100.23

Sample	SiO2	AI2O3	TiO2	FeO	MaO	MnO	CaO	BaO	Na2O	K2O	Total
	%	%	%	%	%	%	%	%	%	%	
981002-7-9	58.46	26.01	0.02	0.30	0.01	0.01	7.77	0.00	7.25	0.04	99.91
981002-7-10	58.60	25.45	0.00	0.29	0.00	0.00	7.21	0.00	7.49	0.03	99.07
981002-7-11	58.65	25.56	0.02	0.43	0.00	0.00	7.42	0.00	7.58	0.03	99.69
981002-7-12	59.91	24.62	0.02	0.18	0.01	0.00	6.39	0.00	7.96	0.05	99.16
981002-7-13	58.59	25.78	0.02	0.19	0.00	0.01	7.65	0.00	7.37	0.04	99.70
981002-7-14	59.39	25.15	0.00	0.39	0.00	0.01	6.93	0.00	7.94	0.03	99.86
981002-7-15	59.56	25.17	0.00	0.24	0.00	0.00	6.88	0.00	7.88	0.04	99.85
981002-7-16	57.96	26.01	0.00	0.28	0.00	0.01	7.90	0.00	7.26	0.05	99.47
981004-24-1	59.99	24.83	0.04	0.24	0.00	0.01	6.49	0.00	7.89	0.10	99.62
981004-24-2	60.01	24.75	0.00	0.29	0.01	0.00	6.58	0.00	7.90	0.09	99.64
981004-24-3	59.36	24.90	0.00	0.19	0.08	0.00	6.66	0.00	7.66	0.19	99.06
981004-24-4	60.67	24.16	0.00	0.11	0.01	0.00	5.48	0.00	7.47	1.39	99.29
981004-24-5	60.23	24.54	0.02	0.21	0.01	0.02	6.14	0.00	8.10	0.10	99.37
981004-24-6	59.52	25.07	0.05	0.19	0.00	0.02	6.65	0.00	7.7 <del>9</del>	0.10	99.40
981004-24-7	59.68	24.88	0.00	0.12	0.00	0.00	6.63	0.00	7.81	0.10	99.23
981004-24-8	59.85	24.62	0.00	0.20	0.00	0.02	6.28	0.00	8.00	0.11	99.12
981004-24-9	59.93	24.71	0.00	0.22	0.02	0.00	6.37	0.00	8.03	0.10	99.37
981004-24-10	59.06	25.04	0.00	0.19	0.00	0.02	7.03	0.00	7.68	0.08	99.17
981004-24-11	59.44	24.82	0.00	0.24	0.00	0.04	6.54	0.00	7.73	0.10	98.93
981004-24-12	59.66	24.71	0.00	0.21	0.00	0.01	6.31	0.00	7.88	0.09	98.90
981004-24-13	58.59	25.34	0.00	0.20	0.00	0.00	7.25	0.00	7.51	0.09	98.97
981004-24-14	59.38	24.95	0.00	0.20	0.00	0.00	6.61	0.00	7.88	0.07	99.12
981009-5-1	61.37	23.61	0.03	0.29	0.00	0.02	5.11	0.00	8.92	0.08	99.43
981009-5-2	61.17	23.54	0.05	0.22	0.00	0.00	5.17	0.00	8.83	0.08	99.06
981009-5-3	61.65	23.84	0.00	0.28	0.00	0.00	5.01	0.00	8.81	0.09	99.66
981009-5-4	61.88	23.72	0.00	0.26	0.01	0.02	5.14	0.00	8.8 <del>9</del>	0.07	100.03
981009-5-5	61.46	23.56	0.01	0.29	0.00	0.01	5.14	0.00	8.79	0.11	99.38
981009-5-6	61.48	23.66	0.04	0.21	0.01	0.00	5.16	0.00	8.80	0.09	99.49
981009-5-7	61.86	23.42	0.03	0.20	0.00	0.00	4.70	0.00	8.82	0.06	99.09

363

981009-5-7

981009-5-9

981009-5-10

981009-5-11

61.86

61.47

61.01

60.78

23.42

23.16

23.50

23.46

0.03

0.00

0.00

0.03

0.20

0.19

0.34

0.27

0.00 Plagioclase (mafic) 5

0.00

0.00

0.00

0.00

0.00

0.00

0.02

4.68

5.02

5.17

0.00

0.00

0.00

8.96

8.94

8.79

98.63

98.90

98.58

0.12

0.08

0.05

Sample	SiO2	AI2O3	TiO2	FeO	MgO	MnO	CaO	BaO	Na2O	K2O	Total
-	%	%	%	%	%	%	%	%	%	%	
981004-15-1	61.48	23.81	0.00	0.18	0.01	0.01	5.04	0.00	8.80	0.09	99.46
981004-15-2	61.80	23.55	0.03	0.11	0.00	0.01	4.83	0.00	8.85	0.08	99.26
981004-15-3	61.76	23.64	0.00	0.11	0.00	0.00	5.07	0.00	8.88	0.09	99.57
981004-15-4	60.17	25.06	0.01	0.11	0.00	0.00	6.38	0.00	8.05	0.07	99.88
981004-15-5	61.63	23.87	0.00	0.11	0.00	0.00	5.22	0.00	8.71	0.05	99.60
981004-15-6	62.04	23.93	0.00	0.16	0.01	0.03	4.84	0.00	8.85	0.06	99.95
981004-15-7	60.89	24.35	0.00	0.18	0.00	0.00	5.67	0.00	8.38	0.06	99.55
981004-15-8	59.57	25.04	0.01	0.15	0.00	0.00	6.47	0.00	7.99	0.09	99.34
981004-15-9	59.76	25.66	0.00	0.15	0.00	0.02	6.91	0.00	7.68	0.06	100.24
981004-15-10	61.89	23.79	0.00	0.21	0.00	0.00	5.22	0.00	8.71	0.05	99.90
981004-15-11	62.44	23.65	0.01	0.16	0.01	0.01	4.78	0.00	9.03	0.07	100.18
981004-15-12	60.25	24.66	0.00	0.31	0.10	0.02	6.47	0.00	7.93	0.08	99.83
981004-15-13	60.75	24.60	0.00	0.29	0.02	0.02	6.10	0.00	8.33	0.07	100.17
981005-5-1	58.31	25.46	0.02	0.19	0.00	0.00	7.19	0.00	7.47	0.11	98.76
981005-5-2	59.01	24.95	0.00	0.21	0.01	0.01	6.67	0.00	7.79	0.10	98.77
981005-5-3	58.82	24.80	0.02	0.18	0.00	0.00	6.61	0.00	7.67	0.11	98.22
981005-5-4	58.89	24.91	0.00	0.21	0.00	0.00	6.57	0.00	7.81	0.13	98.56
981005-5-5	59.99	24.34	0.00	0.22	0.00	0.02	5.82	0.00	8.33	0.12	98.85
981005-5-6	59.42	24.90	0.00	0.19	0.00	0.00	6.42	0.00	7.89	0.11	98.95
981005-5-7	58.94	25.28	0.00	0.1 <del>9</del>	0,01	0.01	7.06	0.00	7.66	0.08	99.24
981005-5-8	58.82	25.07	0.01	0.30	0.00	0.02	6.50	0.00	7.77	0.18	98.70
981005-5-9	60.11	24.08	0.01	0.20	0.01	0.01	5.54	0.00	8.48	0.13	98.55
981005-5-10	60.16	23.91	0.02	0.24	0.00	0.00	5.59	0.00	8.52	0.09	98.57
981005-15-1	56.70	26.41	0.00	0.21	0.00	0.00	8.74	0.00	6.74	0.08	98.90
981005-15-2	57.65	26.03	0.00	0.15	0.00	0,00	8.04	0.00	7.08	0.06	99.01
981005-15-3	57.71	26.33	0.02	0.21	0.00	0.02	8.35	0.00	6.92	0.08	99.65
981005-15-4	58.26	26.36	0.02	0.15	0.00	0.03	8.17	0.00	6.86	0.08	99.92
981005-15-5	57.34	26.58	0.00	0.16	0.00	0.01	8.55	0.00	6.60	0.06	99.30
981005-15-6	57.70	26.55	0.00	0.17	0.00	0.01	8.47	0.00	6.85	0.08	99.83
981005-15-7	37.05	25.52	0.04	2.81	2.91	0.16	23.25	0.00	0.00	0.00	91.82
981005-15-8	38.85	29.52	0.00	4.15	0.00	0.19	23.89	0.00	0.01	0.00	96.60

Plagioclase (mafic) 6

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Sample	SiO2 %	Al2O3 %	TiO2 %	FeO %	MgO %	MnO %	CaO %	BaO %	Na2O %	K2O %	Total
981005-15-9	38.71	28.10	0.03	5.94	0.00	0.16	23 82	0.00	0.00	0.00	06 76
981005-15-10	39.03	29.11	0.03	4.54	0.03	0.18	24.26	0.00	0.00	0.00	90.70
981005-15-11	39.19	29.92	0.00	3.39	0.01	0.15	24.03	0.00	0.00	0.01	96.74
981004-21-1	64.52	22.26	0.00	0.11	0.01	0.00	3 37	0.00	9 71	0 10	100.19
981004-21-2	63.72	22.36	0.00	0.21	0.00	0.00	3 55	0.00	9.78	0.19	00.10
981004-21-6	64.72	22.29	0.03	0.24	0.02	0.00	3 21	0.00	10 14	0.00	39.73 100 77
981004-21-7	65.49	22.51	0.02	0.13	0.00	0.02	3 13	0.00	10.04	0.09	100.77
981004-21-8	64.52	22.43	0.03	0.20	0.00	0.03	3.46	0.00	0.62	0.17	101.52
981004-21-9	64.69	22.61	0.05	0.22	0.00	0.00	3 38	0.00	9.02	0.19	100.40
981004-21-10	65.15	22.30	0.00	0.21	0.01	0.00	3.32	0.00	9.70	0.15	100.89
981004-21-11	66.10	22.55	0.02	0.28	0.01	0.00	3 38	0.00	0.85	0.13	402.25
981004-21-12	66.57	22.48	0.03	0.20	0.00	0.03	3.47	0.00	9.85 9.71	0.13	102.35
981005-9-1	70.47	20.51	0.00	0.22	0.00	0.00	0 44		10.06	0.08	100.00
981005-9-2	66.94	22.50	0.00	0.15	0.00	0.00	2 54		0.90	0.00	102.68
981005-9-3	66.94	22.34	0.00	0.14	0.00	0.00	2.04		9.09	0.12	102.13
981005-9-4	66.89	22.22	0.02	0.11	0.00	0.00	2.49		9.00	0.14	101.74
981005-9-5	66.84	22.42	0.00	0.18	0.00	0.00	2.40		9.70	0.14	101.68
981005-9-6	67.53	22.20	0.00	0.13	0.00	0.01	2.40		9.01	0.14	101.88
981005-9-7	66.67	22.48	0.02	0.10	0.00	0.00	2.50		9.56	0.14	101.98
981005-9-8	65.67	21.99	0.00	0.23	0.00	0.00	2.50		9.95	0.13	101.91
981005-9-9	64.88	21.63	0.00	0.16	0.01	0.01	2.57		9.74	0.09	100.30
981005-9-10	64.92	21.79	0.00	0.11	0.00	0.01	2.00		9.70	0.13	99.23
981005-9-11	64.88	21.96	0.02	0.12	0.01	0.01	2.03		9.01	0.19	99.00
981005-9-12	65.57	21.67	0.00	0.16	0.00	0.00	2.07		9.09	0.19	99.45
981005-9-13	65.37	21.59	0.04	0.09	0.00	0.00	2.30		9.00	0.19	99.78
981005-9-14	66.55	21.89	0.00	0.24	0.00	0.00	2.40		0.11	0.20	99.87
981005-9-15	66.50	22.06	0.01	0.18	0.00	0.00	2.33		9.64	0.11	101.00
981005-9-16	66.04	22.17	0.00	0.10	0.00	0.00	2.25		9.99	0.12	101.15
981005-9-17	66.49	22.27	0.00	0.23	0.00	0.00	2.00		9.04	0.13	100.65
981005- <del>9</del> -18	66.18	22.26	0.01	0.19	0.00	0.00	2.71		9.68	0.13	101.75
981005-9-20	66.41	22.14	0.01	0.19	0.00	0.02	2.50 2.50		9.93	0.17 0.11	101.15 101.36

Sample	SiO2 %	Al2O3 %	<b>TiO2</b> %	FeO %	MgO %	MnO %	CaO %	BaO %	Na2O %	K2O %	Total
981005-9-21	66.35	22.14	0.01	0.17	0.00	0.01	2.42		9.78	0 16	101.06
981005-9-22	65.57	21.99	0.00	0.27	0.00	0.00	2.42		10.09	0.10	100.50
981005-9-23	65.95	22.00	0.00	0.18	0.01	0.00	2.47		9.90	0.12	100.67
981005-7-1	65.53	22.14	0.02	0.15	0.01	0.00	2.81		9.54	0 13	100 42
981005-7-2	66.53	22.34	0.01	0.06	0.00	0.00	2.59		9 71	0.10	101 35
981005-7-3	63.52	22.92	0.00	0.04	0.00	0.00	3.82		8 82	0.30	99.42
981005-7-4	65.06	22.58	0.02	0.15	0.00	0.00	3.14		9.32	0.00	100.46
981005-7-5	66.07	22.21	0.01	0.12	0.00	0.01	2.76		9.70	0.14	101.40
981005-7-6	65.70	22.69	0.01	0.03	0.00	0.01	3.03		9.32	0.15	100.96
981005-7-7	65.52	22.81	0.00	0.05	0.00	0.01	3.24		9 29	0.10	101.00
981005-7-8	63.13	23.50	0.03	0.09	0.00	0.00	4.25		8.63	0.10	99.81
981005-7-9	64.83	22.68	0.00	0.03	0.01	0.00	3.28		9.23	0.29	100 43
981005-7-10	62.91	23.21	0.00	0.09	0.00	0.00	4.14		8.84	0.17	99 41
981005-7-11	65.88	23.08	0.02	0.06	0.00	0.02	3.32		9 42	0.14	101 96
981005-7-12	63.58	22.87	0.00	0.10	0.00	0.00	3.92		8.97	0.14	99 60
981005-7-13	64.95	22.52	0.00	0.08	0.01	0.00	3 22		9.32	0.10	100.20
981005-7-14	65.03	22.20	0.00	0.12	0.00	0.02	2.82		9.69	0.13	100.23
981005-7-15	65.80	21.58	0.00	0.08	0.01	0.00	2.20		9.89	0.22	99.77
981005-7-16	65.02	22.22	0.00	0.16	0.01	0.00	2.79		9.58	0.22	99,77
981005-7-17	65.91	22.68	0.00	0.08	0.00	0.01	2.90		9.40	0.12	101.12
981004-10-1	58.65	25.61	0.04	0.33	0.00	0.01	7 16		7 13	0.07	00.02
981004-10-2	58.45	25.59	0.00	0.27	0.00	0.00	7.37		6 94	0.07	99.02
981004-10-3	61.12	23.99	0.01	0.19	0.00	0.00	5.35		8 20	0.04	90.00
981004-10-4	61.43	23.51	0.00	0.18	0.00	0.00	4 97		8.36	0.00	90.92
981004-10-5	58.31	25.64	0.00	0.28	0.01	0.01	7.53		6.06	0.00	08 78
981004-10-6	59.11	25.23	0.00	0.23	0.00	0.00	6 75		7 39	0.04	90.70
981004-10-7	59.72	24.83	0.01	0.26	0.00	0.03	6 25		7.30	0.03	90.72
981004-10-8	60.72	24.30	0.01	0.21	0.00	0.00	5.68		8.00	0.00	90.90 00 02
981004-10-9	58.21	25.88	0.06	0.21	0.00	0.01	7 67		7.01	0.09	33.UZ 00 11
981004-10-10	63.97	22.34	0.03	0.27	0.02	0.00	3.38		9.40	0.00	99.47

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Sample	SiO2	AI2O3	TiO2	FeO	MaQ	Mag	640	<b>D</b> -0	11.00		
	%	%	%	%	%	%	%	БаО %	wa20 %	K2O	Total
091004 40 44									70	70	
981004-10-11	57.84	26.35	0.03	0.18	0.00	0.00	7.86		6.76	0.06	99 12
981004-10-12	57.70	26.67	0.05	0.14	0.01	0.00	8.00		6.69	0.06	99.35
981004-10-13	59.92	24.94	0.00	0.10	0.00	0.02	6.47		7.57	0.05	99.00
981004-10-14	59.12	25.06	0.00	0.11	0.00	0.00	6.80		7.36	0.00	08.51
981004-10-15	59.77	24.82	0.00	0.08	0.00	0.00	6.42		7.55	0.00	90.01
981004-10-16	60.09	24.28	0.02	0.23	0.00	0.00	5.89		7.00	0.07	90.75
981004-10-17	62.13	23.12	0.04	0.20	0.00	0.00	4 57		8.53	0.00	90.47
981004-10-18	60.09	23.87	0.04	0.17	0.00	0.00	5.62		7.08	0.07	90.09
981004-10-19	59.31	24.38	0.00	0.14	0.00	0.01	6 21		7.50	0.03	97.02
004000 4 4									7.70	0.00	97.00
981009-4-1	53.97	29.01	0.04	0.29	0.00	0.02	11.44		5.05	0.04	99 86
981009-4-2	56.21	27.69	0.00	0.23	0.00	0.00	9.88		5.88	0.05	100.00
981009-4-3	53.20	29.67	0.02	0.21	0.00	0.00	12.03		4 66	0.00	00.82
981009-4-4	52.51	29.96	0.00	0.17	0.00	0.00	12.75		4.00	0.04	99.02 00.64
981009-4-5	54.12	29.12	0.01	0.23	0.00	0.01	11.48		4.21	0.04	99.04
981009-4-6	60.13	25.24	0.02	0.21	0.01	0.02	6.95		7.35	0.00	100.04
981009-4-7	55.08	28.02	0.03	0.30	0.01	0.01	10.56		5 43	0.07	100.09
981009-4-8	61.95	24.51	0.00	0.29	0.00	0.01	5.66		9.45 8.10	0.00	99.49
981009-4-9	60.03	25.38	0.00	0.22	0.00	0.00	6 70		7 61	0.00	100.70
981009-4-10	57.82	26.49	0.00	0.29	0.00	0.00	8 29		6 70	0.07	100.00
981009-4-11	57.53	26.84	0.00	0.29	0.00	0.00	8 56		0.70	0.04	99.63
981009-4-12	56.10	27.65	0.00	0.30	0.01	0.00	0.00		0.30 5 74	0.05	99.85
981009-4-13	51.85	30.11	0.00	0.40	0.00	0.00	12.83		3.74	0.08	99.57
981009-4-14	51.74	30.48	0.03	0.29	0.02	0.00	13 24		4.00	0.06	99.33
074007 4 4									4.00	0.04	33.04
9/100/-1-1	45.90	34.06	0.00	0.21	0.01	0.04	17.77		1 47	0.00	00 45
971007-1-2	44.87	35.21	0.00	0.20	0.00	0.00	18.83		0.83	0.00	39.40 00.06
971007-1-3	46.54	33.94	0.00	0.20	0.00	0.00	17.38		1.69	0.01	99.90
971007-1-4	45.45	34.75	0.01	0.25	0.00	0.00	18 52		1.03	0.02	100.02
9/1007-1-6	47.36	33.45	0.02	0.30	0.00	0.00	16.88		1 08	0.02	100.03
971007-1-7	45.64	34.56	0.00	0.19	0.01	0.01	18 12		1.30	0.02	100.01
971007-1-8	45.83	34.53	0.01	0.24	0.00	0.01	17.82		1.13	0.01	99.67
					0.00	0.01	17.02		1.27	0.00	99.71

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Sample	SiO2 %	Al2O3 %	<b>TiO2</b> %	FeO %	MgO %	MnO %	<b>CaO</b> %	BaO %	Na2O %	K2O %	Total
971007-1-9	46.52	33.96	0.00	0.06	0.00						
971007-1-10	46.57	33.80	0.00	0.20	0.00	0.00	17.50		1.53	0.01	99.83
		00.00	0.02	0.22	0.00	0.03	17.19		1.63	0.00	99.48
NGS-51-205.5-1	57.24	27.15	0.02	0.29	0.00	0.00	0.00				
NGS-51-205.5-2	56.67	27.04	0.00	0.20	0.00	0.00	9.06		6.51	0.05	100.34
NGS-51-205.5-3	56.84	27.08	0.01	0.30	0.01	0.00	9.26		6.49	0.05	99.83
NGS-51-205.5-4	57.23	26.97	0.00	0.00	0.02	0.00	9.18		6.53	0.05	100.00
NGS-51-205.5-5	57.25	26.52	0.00	0.20	0.00	0.04	8.94		6.66	0.07	100.21
NGS-51-205.5-6	58.87	25.37	0.00	0.12	0.00	0.02	8.66		6.82	0.04	99.43
NGS-51-205.5-7	59.21	26.07	0.00	0.25	0.01	0.01	7.36		7.36	0.06	99.28
NGS-51-205.5-8	58.71	25.96	0.00	0.00	0.01	0.01	7.64		7.43	0.06	100.81
NGS-51-205.5-9	58.96	25 75	0.01	0.10	0.00	0.00	7.76		7.28	0.04	99.95
		20.70	0.00	0.15	0.00	0.01	7.48		7.24	0.05	99.65
T95-9-402.7-1	61.01	24.26	0.00	0.15	0.00	0.00	6 70				
T95-9-402.7-2	60.03	24.97	0.00	0.15	0.00	0.00	5.76		8.34	0.07	99.59
T95-9-402.7-3	61.59	24.23	0.00	0.24	0.00	0.01	6.61		7.86	0.07	99.83
T95-9-402.7-4	59.80	25.02	0.00	0.25	0.00	0.01	5.78		8.57	0.07	100.48
T95-9-402.7-5	60.36	24.86	0.00	0.10	0.00	0.00	7.06		7.80	0.08	99.91
T95-9-402.7-6	60,18	24.97	0.00	0.13	0.01	0.00	6.56		7.93	0.06	100.03
T95-9-402.7-7	61.01	23.91	0.00	0.17	0.00	0.01	6.73		8.04	0.07	100.14
T95-9-402.7-8	61.10	24 17	0.00	0.17	0.01	0.01	5.68		8.51	0.08	99.37
T95-9-402.7-9	59.74	25.20	0.00	0.20	0.00	0.01	5.78		8.42	0.07	99.77
T95-9-402.7-10	60.24	24.67	0.02	0.20	0.00	0.02	7.07		7.73	0.06	100.08
T95-9-402.7-11	59.70	24 85	0.02	0.21	0.00	0.00	6.32		7.98	0.07	99.60
			0.00	0.14	0.00	0.01	6.79		7.84	0.07	99,38
981004-26-1	59.33	24.57	0.02	0.15	0.01	0.00					
981004-26-2	60.50	24.07	0.00	0.10	0.01	0.02	6.35		7.86	0.10	98.48
981004-26-3	60.32	24.49	0.02	0.14	0.00	0.00	5.57		8.17	0.07	98.53
981004-26-4	60.01	24.96	0.03	0.14	0.00	0.00	0.20		7.85	0.08	99.11
981004-26-5	59.31	24.82	0.00	0.10	0.00	0.02	6.69		7.77	0.07	99.71
981004-26-9	60,28	24.28	0.00	0.13	0.01	0.00	6.42		7.81	0.09	98.67
981004-26-10	59.40	24.91	0.05	0.11	0.01	0.00	6.05		7.91	0.07	98.73
			0.00	U. 14	0.00	0.00	6.89		7.52	0.08	99.01

#### Hemlo Garnet Probe Data

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 20 nA; 20 s peak counts; 5 um beam.

Total Fe as FeO. Lower detection limits at 2SD are 0.01-0.02 wt %.

Orthoclase-, albite, spessartine, garnet, TiO2 and diopside-based standards for all major elements.

Plagioclase analyses for amphibole-plagioclase geothermometry.

Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Total
	%	%	%	%	%	%	%	%	%	
T95-9-402.7-1	36.69	20.43	0.05	0.07	0.02	32.56	2.45	4.60	2.01	98.88
T95-9-402.7-2	36.49	20.62	0.08	0.03	0.02	33.80	2.45	3.66	1.69	98.84
T95-9-402.7-3	35.65	20.23	0.07	0.06	0.00	33.38	2.17	5.54	1.07	98.17
T95-9-402.7-4	36.18	20.23	0.13	0.00	0.01	33.31	1.91	5.66	1.05	98.47
T95-9-402.7-5	36.41	20.12	0.10	0.05	0.00	32.12	1.75	6.40	1.21	98.16
T95-9-402.7-6	36.15	20.28	0.10	0.08	0.02	33.58	1.94	4.72	1.46	98.33
T95-9-402.7-7	36.52	20.47	0.16	0.05	0.00	33.21	1.79	5.22	1.71	99.14
T95-9-402.7-8	36.46	20.33	0.08	0.00	0.00	33.54	1.79	4.71	1.86	98.76
T95-9-402.7-9	36.26	20.18	0.12	0.07	0.00	33.46	1.75	4.90	1.97	98.70
T95-9-402.7-10	36.17	20.29	0.11	0.05	0.00	33.75	1.67	4.85	2.06	98.94
T95-9-402.7-11	36.68	20.51	0.10	0.00	0.00	32.88	2.26	5.28	1.07	98.78
T95-9-402.7-12	36.42	20.40	0.22	0.04	0.00	33.48	2.01	4.91	1.47	98.94
T95-9-402.7-13	36.58	20.63	0.08	0.12	0.06	32.16	2.27	5.68	1.53	<b>99</b> .11
T95-9-402.7-14	36.68	20.55	0.09	0.00	0.02	32.95	2.24	5.32	1.31	99.16
T95-9-402.7-15	36.41	20.52	0.07	0.05	0.00	33.27	2.02	5.12	1.44	98.90
T95-9-402.7-16	36.07	20.40	0.07	0.06	0.11	34.00	1.99	4.56	1.68	98.93
T95-9-402.7-17	36.22	20.15	0.10	0.06	0.00	33.81	1.98	4.29	2.00	98.59
T95-9-402.7-18	36.40	20.54	0.00	0.02	0.00	33.81	1.91	3.88	2.24	98.80
T95-9-402.7-19	30.59	19.49	0.15	0.04	0.03	35.35	3.06	2.52	1.76	92.99
T95-9-402.7-20	36.43	20.37	0.07	0.00	0.00	33.53	1.90	4.19	2.29	98.77
T95-9-402.7-21	36.29	20.29	0.11	0.00	0.04	32.44	1.78	5.44	2.16	98.56
T95-9-402.7-22	36.28	20.46	0.06	0.01	0.03	33.91	1.87	4.08	2.19	98.89
T95-9-402.7-23	36.24	20.43	0.10	0.00	0.00	33.73	1.94	4.57	1.79	98.80
T95-9-402.7-24	36.22	20.46	0.10	0.01	0.00	33.17	1.88	5.16	1.57	98.55
T95-9-402.7-25	36.43	20.54	0.11	0.05	0.03	33.38	1.92	5.10	1.40	98.96
T95-9-402.7-26	36.30	20.67	0.06	0.02	0.00	33.64	2.03	5.02	1.21	98.95
T95-9-402.7-27	36.34	20.54	0.08	0.03	0.02	32.19	2.09	5.68	1.69	98.66

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Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Total
	%	%	%	%	%	%	%	%	%	
971007-1-2	36.51	20.44	0.10	0.01	0.00	23.83	1.23	11.80	4.51	98.41
971007-1-3	36.76	20.66	0.08	0.07	0.01	25.25	1.45	11.64	2.98	98.8 <del>9</del>
971007-1-4	36.66	20.60	0.14	0.01	0.00	23.51	1.19	13.75	2.23	98.08
971007-1-5	36.89	20.50	0.08	0.00	0.03	24.52	1.20	12.64	2.32	98.17
971007-1-6	36.95	20.41	0.14	0.00	0.09	24.30	1.25	13.21	2.30	98.65
971007-1-7	36.59	20.48	0.07	0.02	0.06	25.04	1.26	11.87	3.04	98.42
971007-1-8	36.73	20.54	0.05	0.03	0.08	22.74	1.06	14.70	2.32	98.24
971007-1- <del>9</del>	36.70	20.51	0.07	0.00	0.08	24.37	1.18	13.62	2.00	98.51
971007-1-10	36.32	20.52	0.07	0.02	0.00	24.88	1.16	12.10	3.34	98.42
971007-1-11	36.69	20.50	0.15	0.02	0.05	24.04	1.12	13.96	1.99	98.51
971007-1-12	36.78	20.14	0,20	0.06	0.13	24.30	1.13	12.75	2.99	98.47
971007-1-13	36.39	20.58	0.15	0.02	0.03	25.84	1.54	10.99	2.51	98.03
971007-1-14	36.48	20.65	0.07	0.00	0.00	27.29	1.80	9.47	2.65	98.41
971007-1-15	36.65	20.64	0.14	0.00	0.04	27.4 <del>9</del>	1.86	9.50	2.65	98.97
971007-1-16	36.67	20.82	0.05	0.00	0.00	27.44	1.85	9.34	2.63	98.81
971007-1-17	36.74	20.77	0.13	0.00	0.05	25.98	1.56	11.17	2.50	98.89
971007-1-18	36.67	20.70	0.08	0.01	0.03	25.50	1.48	11.61	2.08	98.14
970709-4-1	36.51	21.02	0.05	0.04	0.03	32.09	2.62	4.73	2.04	99.12
970709-4-2	36.65	20.84	0.14	0.02	0.06	31.61	2.59	4.45	2.93	99.29
970709-4-3	36.60	20.94	0.05	0.03	0.06	32.22	2.68	4.66	2.08	99.31
970709-4-4	36.56	20.93	0.13	0.03	0.08	30.98	2.54	4.34	3.79	99.38
970709-4-5	36.37	21.04	0.14	0.06	0.05	31.92	2.58	4.62	2.46	99.24
970709-4-6	36.47	20.91	0.03	0.02	0.03	32.12	2.72	4.76	1.76	98.83
970709-4-7	36.46	20.94	0.02	0.00	0.04	33.73	2.63	3.86	1.57	99.24
970709-4-8	36.16	20.75	0.05	0.05	0.06	32.38	2.57	4.36	2.22	98.61
970709-4-9	36.44	20.85	0.04	0.02	0.05	32.85	2.72	3.83	2.41	99.21
970709-4-10	36.33	20.76	0.11	0.01	0.06	32.76	2.65	3.88	1.96	98.50
970709-4-11	36.24	20.74	0.13	0.00	0.02	33.13	2.66	4.12	1.76	98.80
970709-4-12	36.53	20.99	0.03	0.03	0.07	33.62	2.65	3.81	1.56	99.29
970709-4-13	36.35	20.97	0.06	0.04	0.08	33.47	2.67	4.10	1.37	99.11
970709-4-14	36.52	20.99	0.02	0.06	0.06	33.78	2.73	3.88	1.38	99.41
97070 <del>9-4-</del> 15	35.88	20.49	0.70	0.04	0.04	33.16	2.79	3.81	1.74	98.65
97070 <del>9</del> -4-16	36.54	21.02	0.08	0.04	0.08	33.45	2.78	3.26	2.15	99.41
970709-4-17	36.60	20.93	0.06	0.00	0.07	33.60	2.73	3.74	1.74	99.47
970709-4-18	36.37	21.08	0.07	0.00	0.00	33.38	2.73	4.21	1.41	99.24

Metabasite garnets2

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Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	$V_2O_3$	FeO	MgO	CaO	MnO	Total
	%	%	%	%	%	%	%	%	%	
970709-4-1	36.42	20.63	0.04	0.02	0.02	33.30	2.65	4.14	1.37	98.58
970709-4-2	36.19	20.86	0.08	0.03	0.03	33.39	2.52	3.84	1.65	98.58
970709-4-3	36.07	20.36	0.16	0.06	0.02	33.16	2.65	3.93	2.06	98.47
970709-4-4	36.06	20.76	0.06	0.00	0.01	33.21	2.57	4.64	1.29	98.61
970709-4-5	36.09	20.55	0.11	0.03	0.01	32.62	2.62	4.08	2.36	98.46
970709-4-6	36.49	20.76	0.00	0.00	0.00	33.43	2.57	4.13	1.35	98.73
970709-4-7	36.26	20.50	0.16	0.03	0.09	32.38	2.49	3.70	3.25	98.87
970709-4-8	36.40	20.62	0.06	0.02	0.07	32.06	2.63	4.54	2.58	98.97
970709-4-9	36.38	20.63	0.08	0.01	0.00	31.73	2.64	4.35	3.07	98.87
970709-4-10	36.05	20.62	0.14	0.02	0.02	31.79	2.34	3.87	3.87	98.72
970709-4-11	36.10	20.31	0.07	0.00	0.05	32.91	2.40	2.98	3.91	98.74
970709-4-12	36.10	20.62	0.13	0.10	0.09	32.48	2.39	3.24	3.89	99.03
970709-4-13	36.41	20.35	0.07	0.02	0.04	31.79	2.53	3.84	3.75	98.78
970709-4-14	36.17	20.59	0.10	0.03	0.01	31.31	2.56	4.29	3.46	98.53
970709-4-15	24.60	14.67	0.05	0.01	0.00	23.14	1.85	20.45	2.34	87.10
970709-4-16	36.24	20.63	0.03	0.00	0.00	32.01	2.83	4.59	2.13	98.46
970709-4-17	36.19	20.73	0.04	0.00	0.03	33.35	2.60	4.41	1.46	98.81
970709-4-18	36.34	20.51	0.07	0.04	0.00	33.26	2.65	3.87	2.35	99.08
970709-4-19	36.41	20.50	0.08	0.04	0.02	33.24	2.59	4.32	1.32	98.52
970709-4-20	36.47	20.75	0.09	0.04	0.02	33.29	2.55	4.01	1.52	98.74
970709-4-21	36.59	20.61	0.13	0.04	0.03	33.12	2.63	4.21	1.87	99.23

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Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TIO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	MnO	Total
-	%	%	%	%	%	%	%	%	%	
7-35-52.1	36.69	20.93	0.08	0.00	0.04	32.00	2.92	5.75	0.36	98.77
7-35-52.2	36.47	20.76	0.09	0.04	0.02	33.13	2.49	5.35	0.46	98.81
7-35-52.3	36.55	20.76	0.09	0.00	0.02	32.72	2.54	5.56	0.45	98.70
7-35-52.4	36.24	20.79	0.05	0.05	0.04	32.94	2.55	5.60	0.34	98.59
7-35-52.5	36.61	20.72	0.09	0.02	0.00	33.59	2.18	5.60	0.29	99.08
7-35-52.6-6	36.73	20.70	0.09	0.03	0.05	33.14	2.35	5.78	0.33	99.20
7-35-52.6-7	36.57	20.69	0.08	0.00	0.06	32.15	2.75	5.76	0.30	98.35
7-35-52.6-8	36.50	20.93	0.07	0.02	0.01	32.07	2.91	5.51	0.35	98.36
7-35-52.6-9	36.46	20.88	0.07	0.05	0.04	32.09	2.78	6.06	0.34	98.78
7-35-52.6-10	36.55	20.98	0.01	0.03	0.00	32.98	3.17	4.54	0.37	98.63
7-35-52.6-11	36.45	21.17	0.02	0.03	0.00	32.71	3.01	5.10	0.35	98.83
7-35-52.6-12	36.42	20.93	0.03	0.02	0.00	32.65	2.97	5.21	0.39	98.61
7-35-52.6-13	36.55	21.12	0.00	0.06	0.02	33.34	3.15	4.67	0.34	99.24
7-35-52.6-14	36.41	20.96	0.02	0.02	0.03	33.67	3.07	4.38	0.28	<del>9</del> 8.84
7-35-52.6-15	36.33	20.91	0,04	0.00	0.02	33.88	3.14	4.15	0.30	98.76
7-35-52.6-16	36.32	20.89	0,08	0.00	0.01	33.59	3.08	4.41	0.32	98.70
7-35-52.6-17	36.48	21.09	0.06	0.01	0.01	33.17	3.23	4.53	0.34	98.92
7-35-52.1-1	36.49	20.86	0.00	0.03	0.00	33.38	3.26	4.18	0.33	98.53
7-35-52.1-2	36.56	20.79	0.07	0.03	0.04	32.42	2.78	5.86	0.35	98.89
7-35-52.1-3	36.56	20.50	0.09	0.00	0.05	32.73	2.50	5.88	0.32	98.63
7-35-52.1-4	36.19	20.39	0.09	0.06	0.05	33.20	2.42	5.26	0.49	98.16
7-35-52,1-5	35.20	20.13	0.01	0.07	0.02	34.15	3.56	3.67	0.31	97.11
7-35-52.1-6	36.31	20.70	0.03	0.00	0.00	33.90	3.07	4.30	0.28	98,59
7-35-52.1-7	36.50	20.67	0.00	0.04	0.00	33.53	3.17	4.35	0.35	98.61
7-35-52.1-8	36.39	20.52	0.05	0.08	0.00	33.32	3.11	4.39	0.43	98.29
7-35-52.1-9	36.61	20.68	0.02	0.00	0.03	33.15	3.12	4.57	0.39	98.57
7-35-52.1-10	36.56	20.68	0.02	0.00	0.00	32.91	3.14	4.62	0.32	98.24
7-35-52.1-11	36.46	20.38	0.11	0.35	0.00	33.25	2.84	4.55	0.87	98.82
7-35-52,1-12	36.34	20.5 <del>9</del>	0.08	0.06	0.00	32.93	2.59	5.83	0.29	98,70

### Appendix III

### Electron microprobe analyses of mafic fragmental rocks

# Hemlo Plagioclase Probe Data Unpublished probe data from J.R. Clark

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 20 nA; 20 s peak counts, except 45 s for Ba; 5 um beam.

Total Fe as Fe2O3 unless noted. Lower detection limits at 3-sigma 0.02 wt% for Al2O3, MgO and K2O;

0.03 wt% for SiO2, CaO and Na2O; 0.05 wt% for Fe2O3; and 0.06 wt% for BaO.

Orthoclase-, albite, barite, and diopside-based standards for all major elements.

All data from the mafic fragmental unit (Unit 4)

							Weight I	Percent				
Sample	m	Unit	Au int.	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	BaO	Na <sub>2</sub> O	K₂O	Total
			ppm	%	%	%	%	%	%	%	%	%
466Q-13-36.1	36.1	4c	2.20	58.03	26.96	0.04	0.00	8.51	0.05	6.68	0.08	100.35
466Q-13-36.1	36.1	4c	2.20	58.71	26.54	0.07	0.00	8.14	0.07	6.88	0.11	100.51
466Q-13-36,1	36.1	4c	2.20	56.69	27.63	0.08	0.00	9.67	0.09	5.96	0.10	100.21
466Q-13-36.1	36.1	4c	2.20	57.11	27.73	0.04	0.00	9.45	0.07	6.07	0.07	100.53
466Q-13-36.1	36.1	4c	2.20	57.17	27.52	0.04	0.01	9.78	0.09	5.86	0.07	100.53
466Q-13-37.2	37.2	4a	1.50	62.81	23.41	0.10	0.01	4.74	0.10	8.74	0.15	100.05
466Q-13-37.2	37.2	4a	1.50	63.04	23.40	0.07	0.00	4.88	0.13	8.63	0.11	100.25
466Q-13-37.2	37.2	4a	1.50	62.90	23.30	0.14	0.00	4.80	0.15	8.75	0.09	100.12
466Q-13-37.2	37.2	4a	1.50	62.83	23.48	0.35	0.00	4.81	0.16	8.71	0.11	100.44
466Q-13-37.2	37.2	4a	1.50	63.01	23.63	0.06	0.00	4.75	0.13	8.52	0.11	100.20
466Q-13-46.7	46.7	<b>4a</b>	1.10	62.12	24.21	0.07	0.00	5.57	0.00	8.36	0.14	100.45
466Q-13-46.7	46.7	4a	1.10	61.65	24.45	0.06	0.01	5.82	0.00	8.10	0.14	100.21
466Q-13-46.7	46.7	4a	1.10	62.24	24.39	0.06	0.00	5.56	0.00	8.28	0.20	100.73
466Q-13-46.7	46.7	4a	1.10	61.73	24.47	0.06	0.00	5.84	0.00	8.03	0.15	100.27
466Q-13-46.7	46.7	4a	1.10	62.05	24.40	0.07	0.00	5.69	0.01	8.17	0.16	100.55
466Q-13-50.1	50.1	4a	0.30	59.37	26.26	0.04	0.00	7.73	0.02	7.06	0.13	100.61
466Q-13-50.1	50.1	4a	0.30	59.49	25.64	0.07	0.01	7.24	0.10	7.22	0.09	99.85
466Q-13-50.1	50.1	4a	0.30	59.36	26.04	0.11	0.00	7.56	0.04	6.99	0.11	100.21
466Q-13-50.1	<b>50</b> .1	4a	0.30	59.71	25.89	0.05	0.00	7.50	0.06	7.07	0.11	100.37

### Hemlo Phlogopite/Biotite Probe Data

#### Unpublished probe data from J.R. Clark

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 20 nA; 20 s peak counts, except 45 s for Ba; 5 um beam; high-precision quantitative data. Total Fe as FeO unless noted. Lower detection limits at 3-sigma are 0.02 wt% for Al2O3 and MgO; 0.03 wt% for SiO2, Na2O and K2O; 0.04 wt% for CaO; 0.05 wt% for FeO; 0.06 wt% for TiO2; and 0.07 wt% for Cr2O3, V2O3, MnO and BaO.

Orthoclase-, diopside- and garnet-based standards for all major elements. Ti corrected for Ba interference; Cr corrected for V interference. All data from the mafic fragmental unit (Unit 4)

Sample	m	Unit	Au int.	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Cr <sub>2</sub> O <sub>3</sub>	$V_2O_3$	FeO	MnO	MgO	CaO	BaO	Na <sub>2</sub> O	K₂O	Total
-			ppm	%	%	%	%	%	%	%	%	%	%	%	%	%
466Q-13-36.1	36.1	4c	2.20	37.94	2.05	16.58	0.15	0.12	11.67	0.22	16.12	0.00	1.55	0.17	9.58	96.16
466Q-13-36.1	36.1	4c	2.20	38.01	1.99	16.47	0.16	0.09	10.87	0.32	16.89	0.00	1.38	0.14	9.59	95.90
466Q-13-36.1	36.1	4c	2.20	38.12	1.98	16.79	0.08	0.09	10.81	0.32	16.89	0.00	1.40	0.17	9.80	96.46
466Q-13-36.1	36.1	4c	2.20	38.25	1.96	16.55	0.08	0.03	11.22	0.29	16.39	0.00	1.46	0.14	9.64	96.01
466Q-13-36.1	36.1	4c	2.20	37.75	2.02	16.59	0.11	0.07	11.74	0.31	16.66	0.01	1.41	0.14	9.32	96.13
466Q-13-37.2	37.2	4a	1.50	38.00	1.88	18.83	0.21	0.14	8.65	0.20	16.98	0.01	1.48	0,17	10.26	96.80
466Q-13-37.2	37.2	4a	1.50	37.51	1.90	18.28	0.95	0.17	8.83	0.24	16.47	0.04	1.58	0.18	9.99	96 <i>.</i> 15
466Q-13-37.2	37.2	4a	1.50	38.12	2.03	18.39	0.15	0.12	8.75	0.16	16.77	0.04	1.33	0.17	10.09	96.10
466Q-13-37.2	37.2	4a	1.50	38.39	1.73	18.48	0.16	0.15	8.62	0.14	17.11	0.05	1.24	0.16	10.05	96.28
466Q-13-37.2	37.2	4a	1.50	37.47	1.88	18.37	0.73	0.11	8.67	0.15	16.76	0.03	1.57	0,19	10,30	96.21
466Q-13-46.7	46.7	4a	1.10	37,18	1.76	15.90	0.11	0.13	17.09	0.47	12.74	0.03	0.30	0.05	10.24	95.98
466Q-13-46.7	46.7	4a	1.10	37.08	1.49	15.78	0.08	0.14	17.72	0.41	12.73	0.08	0.15	0.09	10.02	95.78
466Q-13-46.7	46.7	4a	1.10	37.28	1.82	16.16	0.04	0.09	17.83	0.47	12.34	0.00	0.34	0.04	10.38	96.78
466Q-13-46.7	46.7	4a	1.10	36.78	1.76	16.32	0.06	0.14	17.88	0.46	12.08	0.00	0.57	0.06	10.21	96.31
466Q-13-46.7	46.7	4a	1.10	37.56	1.79	16.00	0.31	0.14	18.04	0.44	12.18	0.00	0.27	0.02	10.46	97.21
466Q-13-50.1	50.1	4a	0.30	36.54	2.68	17.59	0.06	0.06	16.58	0.30	11.73	0.01	1.70	0.16	9.49	96. <b>8</b> 9
466Q-13-50.1	50.1	4a	0.30	35,94	2.58	17.74	0.01	0.08	16.62	0.28	11.52	0.03	1.73	0.16	9.32	96.00
466Q-13-50.1	50.1	4a	0.30	36,50	2.94	17.17	0.05	0.13	17.52	0.26	11.25	0.00	1.32	0.17	9.81	97.11
466Q-13-50.1	50.1	4a	0.30	36.31	3.00	17.01	0.08	0.15	16.85	0.27	11.28	0.02	1.29	0.17	9.67	96.10
466Q-13-50.1	50.1	4a	0.30	36.47	2.65	17.82	0.08	0.14	16.62	0.28	11.23	0.02	1.62	0.19	9.53	96.64

### Hemlo Epidote Probe Data Unpublished probe data from J.R. Clark

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 20 nA; 20 s peak counts, except 45 s for Ba; 5 um beam; high-precision quantitative data. Total Fe as Fe2O3 unless noted. Lower detection limits at 3-sigma are 0.02 wt% for Al2O3 and MgO; 0.03 wt% for SiO2, CaO, Na2O and K2O;

0.05 wt% for FeO; 0.06 wt% for TiO2, MnO and BaO; and 0.07 wt% for BaO.

Diopside-, orthoclase- and garnet-based standards for all major elements.

All data from the mafic fragmental unit (Unit 4)

Sample	m	Unit	Au int.	SiO <sub>2</sub>	TiO₂	Al <sub>2</sub> O <sub>3</sub>	Cr <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	BaO	Na <sub>2</sub> O	K₂O	Total
			ppm	%	%	%	%	%	%	%	%	%	%	%	%	%
466Q-13-50.1	50.1	4a	0.300	37.55	0.10	24.01	0.00	0.06	12.19	0.35	0.02	22.94	0.00	0.00	0.03	97 25
466Q-13-50.1	50.1	4a	0.300	37.66	0.11	23.87	0.16	0.14	12.28	0.42	0.02	22.85	0.06	0.00	0.02	97 58
466Q-13-50.1	50.1	4a	0.300	37.63	0.04	24.09	0.00	0.02	12.15	0.20	0.01	23.39	0.03	0.00	0.03	97.59
466Q-13-50.1	50.1	4a	0.300	37.81	0.12	24.31	0.07	0.22	12.00	0.42	0.04	22.91	0.01	0.01	0.02	97.93
466Q-13-50.1	50.1	4a	0.300	38.00	0.04	24.62	0.00	0.02	11.82	0.26	0.02	23.47	0.00	0.00	0.01	98.26

### Appendix IV

Other microprobe analyses

# Hemio K-Feidspar Probe Data Unpublished data from J.R. Clark

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 20 nA; 20 s peak counts, except 45 s for Ba; 5 um beam; high-precision que Total Fe as Fe2O3 unless noted. Lower detection limits at 2SD are 0.01-0.02 wt %, except 0.04 wt% for BaO.

Weight Percent

Orthoclase-, albite, barite, and diopside-based standards for all major elements.

Sample	m	Unit	Au int. ppm	Zone	Comments	SiO2 %	Ai2O3 %	Fe2O3 %	MgO %	CaO %	BaO %	Na2O %	K2O %	Total %
440NO-34-11 1	11 1	5b	5.00	1		59 22	20 12	0.02	0.00	0.00	6 50	0.65	14 22	100.73
440NO-34-11 1	11 1	5b	5.00	ĩ		58 99	19.80	0.04	0.00	0.00	6.32	0.68	14.42	100.25
440NQ-34-11 1	11 1	5b	5.00	ĩ	core	58 84	19.96	0.00	0.00	0.00	6.87	0.71	13.84	100.23
440NQ-34-11 1	11 1	5b	5.00	ī	rim	57.40	20.41	0.00	0.01	0.02	9.06	0.60	13.28	100.77
440NQ-34-11.1	11.1	5b	5.00	Ē		58.59	19.75	0.01	0.00	0.00	6.87	0.67	14.03	99.92
440NQ-34-11.1	11.1	5b	5.00	Ē		58.05	19.92	0.03	0.01	0.01	7.77	0.77	13.72	100.27
440NQ-34-11.1	11.1	5b	5.00	Ē		58.12	20.10	0.06	0.00	0.00	7.76	0.70	13.78	100.53
440NQ-34-11.1	11.1	5b	5.00	Ĺ	core	58.54	20.04	0.01	0.00	0.00	7.23	0.50	14.14	100.47
440NQ-34-11.1	11.1	5b	5.00	L	intermed	58.94	20.17	0.04	0.00	0.00	7.07	0.44	14.23	100.90
440NQ-34-11.1	11.1	5b	5.00	L	rim	56.53	20.19	0.03	0.00	0.00	9.11	0.34	13.58	99.78
440NQ-34-11.1	11.1	5b	5.00	L		57.73	20.63	0.00	0.00	0.00	8.59	0.60	13.50	101.04
440NQ-34-12.5	12.5	5d	3.78	L		63.11	18.21	0.00	0.00	0.00	1.23	0.31	17.01	99.86
440NQ-34-12.5	12.5	5d	3.78	L		63.19	18.45	0.00	0.00	0.00	1.00	0.24	17.28	100.15
440NQ-34-12.5	12.5	5d	3.78	L		62.37	18.59	0.00	0.00	0.00	1.84	0.22	17.05	100.06
440NQ-34-12.5	12.5	5d	3.78	L	core	63.80	18.58	0.02	0.00	0.00	0.96	0.20	17.36	100.93
440NQ-34-12.5	12.5	5d	3.78	L	rim	63.73	18.72	0.00	0.01	0.00	1.34	0.26	16.76	100.82
440NQ-34-12.5	12.5	5d	3.78	L		61.18	19.15	0.00	0.00	0.00	3.98	0.42	15.81	100.55
440NQ-34-12.5	12.5	5d	3.78	L		60.85	19.04	0.01	0.01	0.00	4.10	0.55	15.58	100.12
440NQ-34-12.5	12.5	5d	3.78	L		61.47	19.25	0.03	0.00	0.00	4.00	0.37	15.85	100.96
440NQ-34-12.5	12.5	5d	3.78	L	core	61.62	19.05	0.00	0.00	0.00	3.92	0.47	15.69	100.74
440NQ-34-12.5	12.5	5d	3.78	L	rim	61.66	19.16	0.03	0.00	0.00	3.89	0.40	15.71	100.85
440NQ-34-50.2	50.2	4c	0.03		core	63.12	18.16	0.00	0.00	0.01	0.92	0.53	16.93	99.67
440NQ-34-50.2	50.2	4c	0.03		rim	63.05	18.27	0.06	0.00	0.00	0.94	0.42	16.96	99.69
440NQ-34-50.2	50.2	4c	0.03			63.47	18.18	0.01	0.00	0.00	0.70	0.33	17.33	100.03
440NQ-34-50.2	50.2	4c	0.03			62.45	18.02	0.07	0.00	0.03	0.59	0.27	17.43	98.86
440NQ-34-50.2	50.2	4c	0.03			62.87	18.16	0.01	0.00	0.02	0.62	0.48	17.31	99.46

Sample	m	Unit	Au int.	Zone	Comments	SiO2	AI2O3 %	Fe2O3 %	MgO %	CaO %	BaO %	Na2O %	K2O %	Total %
			PP			70	70		/0		~~			
440NQ-34-76.2	76.2	5b	23.20	М		69.56	14.52	0.00	0.00	0.01	5.61	0.14	10.53	100.37
440NQ-34-76.2	76.2	5b	23.20	Μ		57.46	20.02	0.00	0.00	0.04	7.08	0.25	14.25	99.10
440NQ-34-76.2	76.2	5b	23.20	М		58.08	20.24	0.00	0.00	0.00	6.60	0.52	14.58	100.02
440NQ-34-76.2	76.2	5b	23.20	M		57.52	20.22	0.03	0.00	0.02	6.81	0.30	14.49	99.39
440NQ-34-76.2	76.2	5b	23.20	М		56.90	20.00	0.00	0.00	0.01	6.91	0.25	14.26	98.34
440NQ-34-76.2	76.2	5b	23.20	М		57.80	20.16	0.00	0.00	0.01	6.47	0.19	14.47	99.08
440NQ-34-76.2	76.2	5b	23.20	М		57.54	19.53	0.00	0.00	0.24	5.28	0.21	15.05	97.86
440NQ-34-76.2	76.2	5b	23.20	М		56.94	19.87	0.00	0.00	0.00	6.67	0.31	14.28	98.06
440NQ-34-76.2	76.2	5b	23.20	Μ		56.51	19.83	0.00	0.00	0.01	6.94	0.23	14.37	97.88
440NQ-34-76.2	76.2	5b	23.20	Μ	core	58.23	20.18	0.03	0.00	0.00	6.86	0.84	13.65	99,78
440NQ-34-76.2	76.2	5b	23.20	M	rim	57.64	20.16	0.01	0.00	0.01	7.10	0.36	14.28	99.56
440NQ-34-76.2	76.2	5b	23.20	Μ		58.44	20.25	0.00	0.01	0.00	6.74	0.77	13.88	100.09
440NQ-34-76.2	76.2	5b	23.20	М		58.12	20.25	0.00	0.00	0.00	6.96	0.71	13.93	99.97
440NQ-34-76.2	76.2	5b	23.20	Μ		58.27	20.12	0.02	0.00	0.00	6.69	0.33	14.67	100.11
440NQ-34-76.2	76.2	5b	23.20	М		56.94	20.46	0.00	0.01	0.00	7.63	0.66	13.69	99.39
440NQ-34-77.5	77.5	5d	2.58	M	core	60.69	19.31	0.00	0.00	0.00	3.76	0.78	15.40	99.93
440NQ-34-77.5	77.5	5d	2.58	Μ	intermed	61.39	19.02	0.06	0.00	0.00	2.55	0.53	16.03	99.57
440NQ-34-77.5	77.5	5d	2.58	Μ	rim	58.03	19.73	0.04	0.01	0.01	5.86	0.53	14.82	99.03
440NQ-34-77.5	77.5	5d	2.58	М		59.04	19.70	0.00	0.00	0.00	5.05	0.50	15.00	99.30
440NQ-34-77.5	77.5	5d	2.58	М		59.72	19.60	0.00	0.00	0.00	4.65	0.63	15.15	99.74
440NQ-34-77.5	77.5	5d	2.58	М		60.72	19.47	0.01	0.00	0.00	4.20	0.47	15.60	100.46
440NQ-34-77.5	77.5	5d	2.58	M		60.69	19.50	0.01	0.00	0.02	4.36	0.46	15.50	100.55
440NQ-34-77.5	77.5	5d	2.58	М		60.10	19.49	0.01	0.00	0.00	4.66	0.52	15.21	99.99
440NQ-34-77.5	77.5	5d	2.58	M		59.86	19.63	0.03	0.00	0.00	5.14	0.42	15.13	100.20
440NQ-34-77.5	77.5	5d	2.58	М	core	60.12	19.36	0.07	0.00	0.00	4.34	0.66	15.21	99.76
440NQ-34-77.5	77.5	5d	2.58	М	rim	58.56	19.72	0.19	0.00	0.01	5.87	0.58	14.75	99,68
440NQ-34-77.5	77.5	5d	2.58	М		58.15	19.71	0.00	0.01	0.02	6.17	0.66	14.29	99.00
440NQ-34-77.5	77.5	5d	2.58	М		59.18	19.29	0.00	0.00	0.00	4.21	0.62	15.19	98,48
440NQ-34-77.5	77.5	5d	2.58	М		60.00	19.31	0.00	0.00	0.00	4.30	0.72	15.03	99,37
440NQ-34-77.5	77.5	5d	2.58	М		59.51	19.42	0.00	0.00	0.00	4.76	0.47	15.13	99.30
440NO-34-77 5	77 5	5d	2.58	М		59 41	19 39	0.00	0.00	0.00	4 72	0.69	14 85	99.06

Sample	m	Unit	Au int.	Zone	Comments	SiO2	AI2O3	Fe2O3	MgO %	CaO %	BaO %	Na2O %	K2O %	Total %
			pp			<i>,</i> ,,	<i>7</i> 0	<i>,</i> ,,			~			
440NQ-34-80.8	80.8	5b	11.50	Μ		53.00	22.16	0.00	0.00	0.01	14.51	1.39	9.83	100.90
440NQ-34-80.8	80.8	5b	11.50	M		53.05	21.98	0.00	0.00	0.01	13.91	1.47	9.93	100.34
440NQ-34-80.8	80.8	5b	11.50	М		53.99	21.91	0.00	0.02	0.00	12.99	1.29	10.55	100.74
440NQ-34-80.8	80.8	5b	11.50	M		52.40	22.33	0.00	0.01	0.00	14.81	1.47	9.41	100.42
440NQ-34-80.8	80.8	5b	11.50	М	core	52.29	22.22	0.00	0.00	0.00	14.58	1.46	9.65	100.20
440NQ-34-80.8	80.8	5b	11.50	M	rim	49.42	22.38	0.00	0.02	0.00	16.44	1.39	8.67	98.31
440NQ-34-80.8	80.8	5b	11.50	М		52.78	22.13	0.00	0.00	0.00	14.28	1.39	9.73	100.30
440NQ-34-80.8	80.8	5b	11.50	M		51.34	22.40	0.00	0.00	0.00	15.37	1.32	9.35	99.78
440NQ-34-80.8	80.8	5b	11.50	Μ		51.72	21.77	0.00	0.00	0.01	13.83	1.39	9,73	98.45
440NQ-34-80.8	80.8	5b	11.50	Μ	core	52.28	22.11	0.00	0.02	0.02	14.26	1.37	9.81	99.87
440NQ-34-80.8	80.8	5b	11.50	М	rim	51.45	22.39	0.00	0.00	0.00	15.95	1.25	9.43	100.47
440NQ-34-84.8	84.8	3a	6.00	M		58.62	19.99	0.01	0.01	0.00	6.72	1.08	13.60	100.03
440NQ-34-84.8	84.8	3a	6.00	M	Ba-rich rim	55.28	21.06	0.04	0.00	0.02	10.77	1.02	11.80	99.98
440NQ-34-84.8	84.8	3a	6.00	Μ		56.75	19.80	0.00	0.01	0.01	6.98	0.93	13.64	98.13
440NQ-34-84.8	84.8	3a	6.00	М		58.28	19.69	0.02	0.01	0.00	6.00	0.84	14.10	98.94
440NQ-34-84.8	84.8	3a	6.00	Μ		59.95	19.46	0.00	0.00	0.01	5.07	0.96	14.42	99.87
440NQ-34-84.8	84.8	3a	6.00	М	core	58.37	20.32	0.03	0.00	0.00	7.95	0.89	13.19	100.73
440NQ-34-84.8	84.8	3a	6.00	М	intermed	59.82	19.39	0.02	0.00	0.02	4.99	0.90	14.58	99.71
440NQ-34-84.8	84.8	3a	6.00	Μ	rim	55.38	20.52	0.06	0.00	0.04	10.00	0.79	12.50	99.29
440NQ-34-84.8	84.8	3a	6.00	М		58.20	19.78	0.00	0.00	0.00	7.01	0.92	13.52	99.44
440NQ-34-84.8	84.8	3a	6.00	Μ		57.45	20.62	0.01	0.01	0.00	8.52	1.00	12.82	100.43
440NQ-34-84.8	84.8	3a	6.00	Μ		55.43	20.57	0.00	0.00	0.02	10.09	1.11	12.16	99.38
440NQ-34-84.8	84.8	3a	6.00	Μ		56.57	20.65	0.08	0.00	0.00	9.70	0.99	12.31	100.29
440NQ-34-85.3	85.3	5d	38.80	Μ		52.37	22.42	0.00	0.00	0.00	15.01	1.11	10.01	100.92
440NQ-34-85.3	85.3	5d	38.80	М		51.54	22.59	0.00	0.01	0.01	15.19	1.22	9.84	100.39
440NQ-34-85.3	85.3	5d	38.80	М		50.23	22.83	0.00	0.00	0.02	15.64	1.26	9.68	99.67
440NQ-34-85.3	85.3	5d	38.80	Μ		51.63	22.62	0.00	0.00	0.00	15.43	1.16	9.80	100.65
440NQ-34-85.3	85.3	5d	38.80	Μ		51.71	22.51	0.00	0.00	0.01	15.31	1.46	9.54	100.54
440NQ-34-85.3	85.3	5d	38.80	Μ		52.19	22.53	0.00	0.00	0.01	15.35	1.59	9.27	100.94
440NQ-34-85.3	85.3	5d	38.80	Μ		51.98	22.46	0.00	0.00	0.00	15.56	1.13	9.68	100.80
440NQ-34-85.3	85.3	5d	38.80	М		52.16	22.44	0.00	0.00	0.02	15.14	1.56	9.50	100.83

K-feldspar 3

Sample	m	Unit	Au int.	Zone	Comments	SIO2	AI2O3	Fe2O3	MgO	CaO	BaO	Na2O	K2O	Total
			ppm			%	*	%	%	%	%	%	%	%
440NQ-34-85.3	85.3	5d	38.80	М		53.55	21.57	0.04	0.00	0.00	13.38	1.43	10.33	100.31
440NQ-34-85.3	85.3	5d	38.80	Μ		53.19	21.41	0.00	0.01	0.00	13.30	0.82	11.16	99.88
440NQ-34-85.3	85.3	5d	38.80	М	fract zone	52.16	22.07	0.00	0.01	0.00	15.59	1.33	9.53	100.69
440NQ-34-85.3	85.3	5d	38.80	Μ		52.18	22.16	0.03	0.00	0.02	15.38	1.32	9.64	100.72
440NQ-34-85.3	85.3	5d	38.80	М		57.94	19.23	0.00	0.00	0.01	6.30	0.53	14.51	98.52
440NQ-34-85.3	85.3	5d	38.80	М		58.92	19.81	0.00	0.00	0.03	6.85	0.67	14.14	100.43
440NQ-34-85.3	85.3	5d	38.80	М		56.30	20.92	0.01	0.00	0.00	10.70	0.51	12.45	100.87
440NQ-34-86.3	86.3	5d	34.70	Μ		49.59	22.94	0.00	0.00	0.00	16.99	1.41	8.68	99.61
440NQ-34-86.3	86.3	5d	34.70	M		49.52	23.05	0.00	0.00	0.01	16.28	1.52	8.86	99.24
440NQ-34-86.3	86.3	5d	34.70	М		50.07	23.02	0.04	0.01	0.02	16.95	1.58	8.57	100.24
440NQ-34-86.3	86.3	5d	34.70	Μ		51.02	22.96	0.01	0.00	0.02	16.69	1.49	8.71	100.90
440NQ-34-86.3	86.3	5d	34.70	М		52.06	22.53	0.00	0.01	0.01	16.04	1.52	9.12	101.27
440NQ-34-86.3	86.3	5d	34.70	М		51.69	22.60	0.00	0.00	0.01	16.20	1.35	9.04	100.87
440NQ-34-86.3	86.3	5d	34.70	М		51.49	22.78	0.00	0.00	0.00	15.52	1.41	9.32	100.51
440NQ-34-86.3	86.3	5d	34.70	М		52.36	22.18	0.02	0.01	0.00	14.61	1.28	9.65	100.10
440NQ-34-86.3	86.3	5đ	34.70	М		52.50	22.49	0.00	0.00	0.01	15.48	1.22	9.68	101.37
47-5W-02		5d	1.08		core	63.58	18.74	0.01	0.00	0.00	1.25	0.40	16.59	100.57
47-5W-02		5d	1.08		intermed	61.94	18.76	0.00	0.00	0.00	1.29	0.42	16.90	99.31
47-5W-02		5d	1.08		nm	62.86	18.71	0.00	0.00	0.01	1.50	0.36	16.59	100.02
47-5W-02		5d	1.08			62.78	18.98	0.00	0.00	0.00	1.73	0.45	16.47	100.41
47-5W-02		5d	1.08			63.03	18.82	0.00	0.00	0.00	1.75	0.42	16.54	100.56
47-5W-02		5d	1.08		adj Ba-fract	60.68	19.34	0.00	0.00	0.00	3.77	0.41	15.84	100.04
47-5W-02		5d	1.08		core	62.70	18.57	0.01	0.00	0.00	1.40	0.40	16.83	99.92
47-5W-02		5d	1.08		rim	62.27	18.85	0.00	0.00	0.01	1.91	0.42	16.66	100.14
47-5W-02		5d	1.08			62.52	18.72	0.00	0.00	0.01	1.47	0.39	17.00	100.12
47-5W-02		5d	1.08			62.34	18.62	0.00	0.00	0.00	1.26	0.26	17.21	<b>99</b> .70
47-5W-02		5d	1.08		adj Ba-fract	61.66	19.03	0.03	0.00	0.00	2.96	0.25	16.30	100.22
47-5W-03		3a	0.98		core	61.63	19.03	0.00	0.00	0.00	2.30	0.55	16.22	99.73
47-5W-03		3a	0.98		rim	61.49	19.12	0.02	0.00	0.00	2.26	0.50	16.15	99.53
47-5W-03		3a	0.98			62.38	19.01	0.00	0.00	0.02	2.28	0.50	16.28	100.50
47-5W-03		3a	0.98			61.18	19,39	0.00	0.00	0.00	3.44	0.24	16.19	100.44
47-5W-03		3a	0.98			61.33	19.37	0.02	0.00	0.00	3.31	0.56	15.77	100.36

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Sample	m	Unit	Au int. ppm	Zone	Comments	SiO2 %	AI2O3 %	Fe2O3 %	MgO %	CaO %	BaO %	Na2O %	K2O %	Total %
47-5W-03		3a	0.98			61.77	19.02	0.00	0.00	0.00	2.19	0.53	16.33	99.83
47-5W-03		3a	0.98			61.64	19.11	0.00	0.00	0.00	2.17	0.55	16.23	99.70
47-5W-03		3a	0.98			61.86	19.20	0.00	0.00	0.00	2.37	0.40	16.38	100.21
47-5W-03		3a	0.98			60.73	19.05	0.01	0.00	0.02	2.29	0.44	16.09	98.63
47-5W-04		5j	0.42		core	61.21	19.18	0.02	0.00	0.00	3.01	0.61	15.58	99.62
47-5W-04		<b>5</b> j	0.42		rim	60.97	19.11	0.00	0.00	0.00	2.76	0.37	16.26	99.47
47-5W-04		<b>5</b> j	0.42			61.34	19.08	0.01	0.00	0.02	2.92	0.51	15.81	99.70
47-5W-04		<b>5</b> j	0.42			62.56	18.83	0.02	0.00	0.00	1.92	0.61	16.31	100.26
47-5W-04		<b>5</b> j	0.42			61.98	18.97	0.01	0.00	0.00	2.27	0.58	15.85	99.66
47-5W-04		5j	0.42			61.18	19.02	0.01	0.00	0.00	2.84	0.58	15.82	99.45
47-5W-04		5j	0.42			61.80	18.99	0.07	0.00	0.00	2.64	0.47	16.13	100.09
47-5W-04		5	0.42			62.16	18.57	0.00	0.00	0.01	1.04	0.44	16.58	98.79
47-5W-04		5j	0.42			62.34	18.61	0.00	0.00	0.00	0.98	0.42	16.86	99.21
47-5W-04		5j	0.42			62.30	18.56	0.05	0.00	0.00	1.01	0.40	16.79	99.11
47-5W-08B		5a	0.92		core	61.69	18.86	0.01	0.00	0.00	2.46	0.58	16.18	99.77
47-5W-08B		5a	0.92		intermed	62.76	18.93	0.00	0.00	0.00	2.14	0.38	16.64	100.85
47-5W-08B		5a	0.92		rim	62.94	18.75	0.04	0.00	0.00	0.89	0.18	17.31	100.12
47-5W-08B		5a	0.92			62.57	18.77	0.01	0.00	0.00	1.59	0.30	17.01	100.24
47-5W-08B		5a	0.92			61.73	18.88	0.00	0.01	0.00	2.43	0.55	16.19	99.79
47-5W-08B		5a	0.92			61.88	18.86	0.00	0.03	0.00	2.43	0.42	16.43	100.04
47-5W-08B		5a	0.92		core	62.48	18.82	0.00	0.00	0.00	1.83	0.53	16.53	100.18
47-5W-08B		5a	0.92		rim	61.70	18.87	0.01	0.02	0.00	2.34	0.48	16.42	99.84
47-5W-08B		5a	0.92			62.00	18.87	0.04	0.00	0.00	2.26	0.51	16.48	100.15
47-5W-08B		5a	0.92			61.02	18.75	0.02	0,00	0.01	2.11	0.40	16.58	98.89
47-5W-08B		5a	0.92			61.65	18.61	0.01	0.01	0.00	2.07	0.54	16.41	99.29
47-5W-08B		5a	0.92			62.15	19.04	0.00	0.00	0.00	2.37	0.38	16.47	100.41

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Sample	m	Unit	Au int. ppm	Zone	Comments	SIO2 %	Al2O3 %	Fe2O3 %	MgO %	CaO %	BaO %	Na2O %	K2O %	<b>Total</b> %
460-109-45.7	45.7	10a	180.90	М		63.51	18.40	0.00	0.00	0.00	1.05	0.31	17.01	100.28
460-109-45.7	45.7	10a	180.90	Μ	core	63.78	18.45	0.00	0.00	0.00	0.98	0.49	16.86	100.57
460-109-45.7	45.7	10a	180.90	Μ	rim	60.34	19.34	0.17	0.28	0.01	1.16	0.25	16.46	98.02
460-109-45.7	45.7	10a	180.90	М		63.62	18.45	0.05	0.00	0.00	1.12	0.52	16.67	100.42
460-109-45.7	45.7	10a	180.90	Μ		63.05	18.41	0.02	0.00	0.00	1.18	0.51	16.73	99,90
460-109-45.7	45.7	10a	180.90	Μ		63.02	18.78	0.00	0.00	0.05	1.89	0.84	16.18	100.75
460-109-45.7	45.7	10a	180.90	Μ	core	63.73	18.46	0.04	0.00	0.00	1.09	0.50	16.72	100.53
460-109-45.7	45.7	10a	180.90	Μ	rim	62.78	18.81	0.01	0.00	0.00	2.05	0.58	16.23	100.47
460-109-45.7	45.7	10a	180.90	Μ		63.76	18.45	0.00	0.00	0.00	1.05	0.35	16.99	100.58

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# Hemlo Phlogopite/Biotite Probe Data (ore zone) Unpublished biotite data from J.R. Clark

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 20 nA; 20 s peak counts, except 45 s for Ba; 5 um beam; high-precision quantitative data. Total Fe as FeO unless noted. Lower detection limits at 2SD are 0.01-0.03 wt %, except 0.04 wt% for TiO2, MnO, V2O3, Cr2O3 and BaO. Orthoclase-, diopside- and gamet-based standards for all major elements. Ti corrected for Ba interference; Cr corrected for V interference.

Sample	m	Unit	Au int.	Zone	Comments	SiO2	TiO2	Al2O3	Cr2O3	V2O3	FeO	MnO	MgO	CaO	BaO	Na2O	K2O	Total
			ppm			%	%	%	%	%	%	%	%	70	70	%	%	70
5-13-26.2	26.2	5d	24.800	М	core	38.61	0.84	16.06	0.01	3.43	4.86	0.05	19.17	0.01	2.17	0.16	9.79	95,16
5-13-26.2	26.2	5d	24.800	Μ	rim	39.14	0.80	15.49	0.00	2.52	4.92	0.06	20.04	0.03	1.77	0.15	9.63	94.54
5-13-26.2	26.2	5d	24.800	М		38,78	0.88	16.08	0.00	3.49	4.83	0.08	18.85	0.00	2.27	0.17	9.77	95.20
5-13-26.2	26.2	5d	24,800	м	core	37.56	1.61	16.36	0.24	2.57	4.75	0.05	19.04	0.01	1.94	0.17	9.85	94.13
5-13-26.2	26.2	5d	24.800	М	rim	39.61	1.30	17.57	0.24	2.10	4.03	0.04	17.71	0.00	1.85	0.16	9.79	<del>9</del> 4.40
440NQ-34-4.3	4.3	2a	0.002			36.17	1.64	19.57	0.15	0.05	15.38	0.16	11.67	0.05	0.27	0.15	10.25	95.51
440NQ-34-4.3	4.3	2a	0.002			35.40	1.49	20.21	0.16	0.09	16.21	0.20	11.59	0.05	0.18	0.11	9.16	94.83
440NQ-34-4.3	4.3	2a	0.002			35.35	1.63	19.32	0.20	0.14	16.37	0.10	11.97	0.11	0.19	0.12	9.19	94.71
440NQ-34-4.3	4.3	2a	0.002			36.08	1.62	19.48	0.05	0.08	16.27	0.15	11.38	0.04	0.19	0.15	10.15	95.64
440NQ-34-4.3	4.3	2a	0.002			36.25	1.55	19.49	0.00	0.09	16.07	0.15	11.52	0.00	0.20	0.16	10.22	95.70
440NQ-34-4.3	4.3	2a	0.002			35.74	1.58	19.46	0.16	0.09	15,97	0.11	11.81	0.01	0.14	0.10	9.14	94.30
440NQ-34-50.2	50.2	4c	0.033			37.78	1.53	16.42	0.02	0.15	13.20	0.36	14.71	0.06	0.01	0.05	10.64	94.92
440NQ-34-50.2	50.2	4c	0.033			38.14	1.39	16.11	0.03	0.17	12.50	0.31	15.42	0.01	0.00	0.08	10.40	94.56
440NQ-34-50.2	50.2	4c	0.033			37.52	1.63	16.17	0.03	0.12	13.25	0.34	15.81	0.01	0.07	0.06	9.85	94.87
440NQ-34-50.2	50.2	4c	0.033			38.39	2.05	16.31	0.05	0.25	13.00	0.37	14.78	0.00	0.06	0.06	10.81	96.12
440NQ-34-50.2	50.2	4c	0.033			36.82	1.49	17.40	0.00	0.19	16.30	0.33	12.41	0.01	0.00	0.04	10.59	95.58
440NQ-34-50.2	50.2	4c	0.033			37.03	2.39	16.24	0.00	0.24	16.34	0.36	12.38	0.02	0.05	0.06	10.37	95.46
440NQ-34-50.2	50.2	4c	0.033			37.93	1.57	17.03	0.04	0.16	14.63	0.36	13.80	0.01	0.06	0.08	10.84	96.50
440NQ-34-50.2	50.2	4c	0.033			37.35	1.82	16.15	0.00	0.19	15.29	0.47	13.49	0.02	0.10	0.08	10.60	95.57
440NQ-34-80.8	80.8	5b	11.500	М		37.28	1.66	17.43	0.20	1.74	4.72	0.10	18.96	0.01	3.45	0.14	9.53	95.23
440NQ-34-80.8	80.8	5b	11.500	М		37.56	1.19	17.72	0.19	1.14	4.03	0.09	20.27	0.00	3.03	0.13	9.38	94.72
440NQ-34-80.8	80.8	5b	11.500	М		37.94	1.33	17.94	0.22	1.20	4.59	0.10	20.30	0.04	2.94	0.15	9.64	96.39
440NQ-34-84.8	84.8	3a	6.000	м		39.26	1.21	18.53	0.00	0.07	3.45	0.16	21.15	0.01	0.35	0.09	11.08	95.34
440NQ-34-84.8	84.8	3a	6.000	м		39.21	1.00	17.43	0.01	0.05	3,57	0.15	21.13	0.03	0.69	0.14	10.60	94.00
440NQ-34-84.8	84.8	3a	6.000	М		39.34	1.29	17.57	0.02	0.10	3.85	0.16	20.88	0.01	0.75	0.10	10.68	94.75
440NQ-34-84.8	84.8	3a	6.000	М		39.54	1.27	17.42	0.02	0.03	3.86	0.20	21.12	0.00	0.84	0.08	10.56	94.92
440NQ-34-85.3	85.3	5d	38,800	M		39.58	0.94	17.59	0.03	0.43	1.23	0.16	22.72	0.01	1.65	0.15	10.19	94.67
440NQ-34-85.3	85.3	5d	38.800	M	core	39.33	1.12	17.68	0.06	0.54	1,40	0.18	22.37	0.00	1.80	0.13	10.38	94.99
440NQ-34-85.3	85.3	5d	38.800	М	rim	39.30	0.75	17.26	0.07	0.44	0.95	0.11	24.03	0.01	1.31	0.14	9.62	93.97

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Sample	m	Unit	Au int. ppm	Zone	Comments	SiO2 %	TiO2 %	Al2O3 %	Cr2O3 %	V2O3 %	FeO %	MnO %	MgO %	CaO %	BaO %	Na2O %	K2O %	Total %
440NO-34-85 3	85 3	54	38 800	м		30 48	1 10	17.66	0.04	0.53	1 53	0 12	22.66	0.00	1.58	0 14	10 42	95 25
440NO-34-85 3	85.3	54	38.800	M		39.58	1 18	17.00	0.04	0.00	1 48	0.12	22.64	0.00	1.65	0.13	10.37	95.32
440NO-34-85 3	85.3	5d	38 800	M		39.70	1 23	17 18	0.02	0.70	1.48	0.10	22.39	0.00	1.58	0.14	10.32	94.87
440NQ-34-85 3	85.3	5d	38,800	M		39.58	1.33	17.08	0.00	0.86	1.46	0.15	22.16	0.00	1.58	0.16	10.23	94.58
440NQ-34-85 3	85.3	5d	38 800	M		38.69	1.09	17.44	0.03	1.31	1.12	0.21	22.18	0.01	1.82	0.14	10.24	94.28
440NQ-34-85 3	85.3	5d	38 800	M		39.27	1.13	17.34	0.03	0.73	1.35	0.12	22.73	0.02	1.74	0.14	10.21	94.80
440NQ-34-86 3	86.3	5d	34 700	M		38 52	1 32	17.54	0.00	1.92	1.53	0.11	21.76	0.00	2.68	0.14	9.95	95.47
440NO-34-86 3	86.3	5d	34 700	M		38.98	1.18	17.15	0.03	1.48	1.68	0.11	22.05	0.00	2.35	0.12	10.07	95.19
440NQ-34-86 3	86.3	5d	34,700	M		38.87	1.36	17.00	0.00	2.23	1.39	0.16	21.63	0.00	2.29	0.14	10.07	95, 15
440NQ-34-86.3	86.3	5d	34,700	M		38.50	1.36	16.95	0.00	2,19	1.94	0.16	21.13	0.02	2.38	0.12	10.09	94.83
440NQ-34-86.3	86.3	5d	34,700	M		38.56	1.35	16.82	0.00	1.99	1.54	0.16	21.38	0.02	2.58	0.15	9.87	94.42
440NQ-34-88.4	88.4	7e	2,350	M		38.73	1.55	19.14	0.00	0.03	5.26	0.33	19.27	0.04	0.28	0.16	10.33	95.12
440NQ-34-88.4	88.4	7e	2.350	M		38,59	1.43	19.36	0.04	0.11	5.27	0.29	19.50	0.00	0.23	0.16	10.25	95.21
440NQ-34-88.4	88.4	7e	2.350	M		38.76	1.23	19.33	0.00	0.01	5.33	0.38	19.33	0.02	0.25	0.17	10.41	95.22
440NQ-34-88.4	88.4	7e	2.350	м		38,60	1.16	19.13	0.01	0.06	5.34	0.29	19.69	0.00	0.21	0.18	10.31	94.97
440NQ-34-88.4	88.4	7e	2.350	м		38.77	1.14	19.28	0.04	0.02	5.41	0.32	19.64	0.00	0.20	0.18	10.37	95.37
440NQ-34-90.9	90.9	7e	1.000	М		39.70	0.67	18.34	0.00	0.11	3.31	0.12	21.78	0.00	0.38	0.26	10.65	95.31
440NQ-34-90.9	90.9	-7e	1.000	м		39.51	0.74	18.15	0.02	0.02	3.05	0.15	21.73	0.03	0.41	0.31	10.53	94.65
440NQ-34-90.9	90.9	7e	1.000	м	core	39.89	0.85	18.45	0.04	0.05	3.25	0.16	21.60	0.00	0.34	0.34	10.36	95.35
440NQ-34-90.9	90.9	7e	1.000	м	rim	39,58	0.82	18.28	0.00	0.10	3,16	0.18	21.65	0.00	0.34	0.29	10.36	94,76
440NQ-34-90.9	90.9	7e	1.000	м	core	39.97	0.55	18.39	0.02	0.09	3.17	0.13	21.34	0.00	0.33	0.25	10.48	94.72
440NQ-34-90.9	90.9	7e	1.000	М	rim	39.40	0.61	18.36	0.03	0.08	3.19	0.16	22.45	0.02	0.31	0.22	10.02	94. <b>8</b> 5
47-5W-04		5j	0.416			39.15	0.97	16.17	0.09	0.67	5.74	0.11	19.66	0.00	0.05	0.07	10.83	93.52
47-5W-04		5j	0.416			38.76	1.07	16.22	0.12	0.63	5.60	0.15	19.46	0.02	0.10	0.05	10.77	92.93
47-5W-04		5j	0.416			3 <del>9</del> .74	0.98	16.25	0.17	0.68	5.78	0.17	20.01	0.00	0.06	0.06	11.01	94.91
47-5W-04		5j	0.416			39.49	0.91	15.76	0.10	0.70	5.37	0.17	20.82	0.00	0.09	0.05	10.19	93.66
47-5W-08B		5a	0.920			40.30	1.31	15.89	0.26	1.37	2.69	0.18	21.00	0.00	0.20	0.09	11.18	<del>94</del> .48
47-5W-08B		5a	0.920			40.38	1.15	15.84	0.26	1.23	2.73	0.12	21.65	0.00	0.22	0.09	11.37	95.04
47-5W-08B		5a	0.920			40.13	1.19	16.32	0.29	1.46	2.74	0.24	20.59	0.00	0.20	0.09	11.10	94.33
47-5W-08B		5a	0.920			40.13	1.19	16.19	0.25	1.14	2.90	0.16	21.41	0.00	0.25	0.09	11.19	94.90
47-5W-08B		5a	0.920			40.02	1.14	15.96	0.23	1.27	2.93	0.11	20.70	0.00	0.21	0.09	11.35	94.00
460-109-45.7	45.7	10a	180.900	м		39.08	1.28	17.13	0.16	0.73	6.13	0.22	19.36	0.04	0.07	0.10	10.97	95.26
460-109-45 7	45.7	10a	180 900	м		39.24	1.13	17.33	0.07	0.59	6.21	0.18	19.41	0.00	0.08	0.09	10.87	95.18

### Hemlo Muscovite Probe Data

#### Unpublished probe data from J.R. Clark

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 20 nA; 20 s peak counts, except 45 s for Ba; 5 um beam; high-precision quantitative data. Total Fe as FeO unless noted. Lower detection limits at 2SD are 0.01-0.03 wt %, except 0.04 wt% for TiO2, MnO, V2O3, Cr2O3 and BaO.

Ti values corrected for Ba interference; Cr values corrected for V interference.

Orthoclase-, diopside- and garnet-based standards for all major elements.

Sample	m	Unit	Au int.	Comments	SiO2	TiO2	AI2O3	Cr2O3	V2O3	FeO	MnO	MgO	CaO	BaO	Na2O	K2O	Total
-			ppm		%	%	%	%	%	%	%	%	%	%	%	%	%
5-13-26.2	26.2	5i	24.80		41.63	0.61	28.32	0.02	5.69	1.43	0.04	2.06	0.00	6.55	0.32	8.79	95.47
5-13-26.2	26.2	5i	24.80		41.02	0.57	27.83	0.01	6.02	1.33	0.08	2.14	0.01	8.18	0.32	8.24	95.74
5-13-26.2	26.2	5i	24.80		40.20	0.50	28.10	0.02	6.38	1.55	0.00	2.20	0.03	7.99	0.34	8.23	95.55
5-13-26.2	26.2	<b>5</b> i	24.80		41.28	0.84	30.28	0.02	3.35	1.57	0.00	2.04	0.00	7.64	0.37	8.46	95.85
5-13-26.2	26.2	5i	24.80		40.63	1.33	25.88	0.38	6.97	1.50	0.00	2.29	0.02	5.91	0.32	8.97	94.18
5-13-26.2	26.2	5i	24.80	core	41.28	1.34	24.85	0.12	8.00	1.69	0.03	2.29	0.00	6.09	0.31	8.85	94.86
5-13-26.2	26.2	<b>5</b> i	24.80	rim	41.22	1.05	25.76	0.25	7.89	1.96	0.02	2.35	0.00	5.54	0.33	9.04	95.41
440NQ-34-4.3	4.3	2a	0.00		45.70	0.02	35.68	0.01	0.00	1.27	0.07	0.28	0.07	0.00	0.57	10.79	94.44
440NQ-34-4.3	4.3	2a	0.00		45,76	0.26	34.73	0.00	0.04	2.05	0.00	0.55	0.00	0.29	0.68	11.13	95.48
440NQ-34-4.3	4.3	2a	0.00		45.20	0.42	35.00	0.00	0.08	2.04	0.03	0.65	0.03	0.24	0.94	10.72	95.33
440NQ-34-4.3	4.3	2a	0.00		45.70	0.41	35.06	0.01	0.02	2.21	0.04	0.62	0.01	0.27	0.97	10.62	95.94
440NQ-34-11.1	11.1	5b	5.00	core	44.97	1.13	32.72	0.07	0.28	0.24	0.00	1.63	0.00	2.33	0.62	10.46	94.44
440NQ-34-11.1	11.1	5b	5.00	rim	45.06	0.99	31.95	0.03	0.33	0.29	0.00	1.64	0.03	2.29	0.36	10.83	<b>9</b> 3.7 <b>9</b>
440NQ-34-11.1	11.1	5b	5.00		45.24	0.91	32.61	0.00	0.25	0.27	0.01	1.67	0.00	2.25	0.55	10.59	94.34
440NQ-34-11.1	11.1	5b	5.00		45.07	1.20	32.65	0.01	0.25	0.23	0.01	1.63	0.00	2.14	0.61	10.48	94.28
440NQ-34-11.1	11.1	5b	5.00		45.13	1.08	32.43	0.01	0.25	0.31	0.02	1.73	0.02	2.44	0.50	10.75	94.67
440NQ-34-11.1	11.1	5b	5.00		44.95	1.22	32.60	0.04	0.26	0.29	0.01	1.63	0.00	1.96	0.56	10.79	94.29
440NQ-34-11.1	11.1	5b	5.00		45.36	1.31	32.22	0.03	0.39	0.29	0.01	1.74	0.00	2.26	0.59	10.46	94.66
440NQ-34-11.1	11.1	5b	5.00		45.40	1.42	32.76	0.04	0.39	0.30	0.00	1.64	0.00	2.40	0.52	10.50	<b>9</b> 5.36
440NQ-34-11.1	11.1	5b	5.00		45.37	0.97	32.68	0.00	0.15	0.27	0.00	1.71	0.02	2.72	0.48	10.49	94.84
440NQ-34-11.1	11.1	5b	5.00		45.76	1.11	32.50	0.00	0.14	0.33	0.02	1.85	0.00	2.09	0.51	10.88	95.18
440NQ-34-11.1	11.1	5b	5.00		45.75	1.15	33.03	0.03	0.13	0.31	0.00	1.60	0.01	2.19	0.49	10.82	95.50
440NQ-34-11.1	11.1	5b	5.00		46.21	0.68	32.45	0.00	0.19	0.36	0.02	1.84	0.00	2.02	0.25	11.35	<b>95.36</b>
440NQ-34-11.1	11.1	5b	5.00		45,46	1.22	33.06	0.03	0.18	0.22	0.04	1.69	0.00	1.94	0.55	10.73	<b>95.11</b>
440NQ-34-11.1	11.1	5b	5.00		45.35	1.40	33.03	0.00	0.24	0.27	0.01	1.69	0.00	1.94	0.56	10.69	95.18

Sample	m	Unit	Au int.	Comments	SiO2	TiO2	AI2O3	Cr2O3	V2O3	FeO	MnO	MgO	CaO	BaO	Na2O	K2O	Total
			ppm		%	%	%	%	%	%	%	%	%	%	%	%	%
440NQ-34-11.1	11.1	5b	5.00		45.34	1.03	33.11	0.00	0.16	0.24	0.04	1.80	0.00	2.38	0.57	10.55	95.21
440NQ-34-11.1	11.1	5b	5.00		45.39	1.06	33.09	0.00	0.07	0.27	0.00	1.83	0.00	2.46	0.54	10.50	95.21
440NQ-34-11.1	11.1	5b	5.00		44.97	1.27	32.84	0.01	0.14	0.26	0.05	1.68	0.00	2.21	0.54	10.58	94.55
440NQ-34-11.1	11.1	5b	5.00		45.49	1.41	33.25	0.00	0.13	0.24	0.00	1.72	0.01	2.00	0.57	10.77	95.58
440NQ-34-11.1	11.1	5b	5.00		45.58	1.30	32.92	0.03	0.12	0.21	0.04	1.74	0.00	2.11	0.57	10.52	95.15
440NQ-34-12.5	12.5	5d	3.78	соге	47.99	1.24	31.86	0.01	0.40	0.29	0.00	2.12	0.01	0.32	0.35	11.74	96.34
440NQ-34-12.5	12.5	5d	3.78	rim	47.17	1.29	32.56	0.00	0.28	0.28	0.01	1.93	0.00	0.36	0.39	11.63	95.90
440NQ-34-12.5	12.5	5d	3.78		46.74	1.73	31.92	0.00	0.62	0.39	0.03	1.87	0.02	0.32	0.47	11.57	95.67
440NQ-34-12.5	12.5	5d	3.78		47.98	1.27	31.35	0.00	0.80	0.33	0.00	2.25	0.00	0.40	0.41	11.54	96.34
440NQ-34-12.5	12.5	5d	3.78		45.86	1.42	30.05	0.08	2.51	0.83	0.00	2.00	0.02	1.31	0.47	11.16	95.70
440NQ-34-12.5	12.5	5d	3.78		45.73	1.45	29.33	0.07	2.54	0.84	0.00	1.99	0.01	1.22	0.33	10.93	94.45
440NQ-34-12.5	12.5	5d	3.78	core	45.86	1.36	28.91	0.02	2.14	0.82	0.03	2.25	0.00	0.58	0.26	11.31	93.53
440NQ-34-12.5	12.5	5d	3.78	rim	45.62	1.46	30.45	0.06	2.36	0.84	0.02	2.00	0.01	1.39	0.40	11.07	95.67
440NQ-34-50.2	50.2	4c	0.03		47.27	0.49	30.32	0.01	0.00	2.57	0.04	1.83	0.05	0.06	0.26	11.83	94.72
440NQ-34-50.2	50.2	4c	0.03		47.16	0.55	30.69	0.00	0.10	3.15	0.04	2.00	0.03	0.03	0.18	11.97	95.89
440NQ-34-50.2	50.2	4c	0.03	core	47.67	1.49	30.13	0.01	0.30	3.52	0.01	1.59	0.01	0.18	0.25	11.59	96.73
440NQ-34-50.2	50.2	4c	0.03	rim	45.10	0.68	29.75	0.00	0.21	3.65	0.06	1.51	0.05	0.15	0.25	11.80	93.20
440NQ-34-50.2	50.2	4c	0.03		47.09	1.43	31.71	0.01	0.20	2.05	0.04	1.63	0.03	0.25	0.29	11.70	96.44
440NQ-34-50.2	50.2	4c	0.03		46.57	1.27	32.01	0.02	0.23	2.43	0.02	1.29	0.04	0.27	0.29	11.48	95.93
440NQ-34-50.2	50.2	4c	0.03	py shadow	47.37	0.55	31.00	0.04	0.14	2.89	0.04	1.84	0.02	0.09	0.29	11.69	95.96
440NQ-34-50.2	50.2	4c	0.03	py shadow	46.79	0.37	30.85	0.07	0.17	2.90	0.04	1.98	0.03	0.06	0.33	11.57	95.16
440NQ-34-76.2	76.2	5b	23.20		45.85	1.46	33.15	0.00	0.13	0.34	0.00	1.95	0.00	2.20	0.47	10.62	96.17
440NQ-34-76.2	76.2	5b	23.20		45.58	1.42	33.41	0.04	0.20	0.37	0.00	1.73	0.01	2.13	0.37	10.92	96.19
440NQ-34-76.2	76.2	5b	23.20		45.87	1.47	33.50	0.01	0.12	0.35	0.01	1.78	0.00	2.00	0.51	10.82	96.43
440NQ-34-76.2	76.2	5b	23.20		45.61	1.42	33.13	0.00	0.15	0.37	0.03	1.86	0.00	2.01	0.48	10.74	95.79
440NQ-34-76.2	76.2	5b	23.20		45.36	1.31	31.36	0.01	0.47	0.31	0.01	2.18	0.00	1.99	0.32	10.94	94.26
440NQ-34-76.2	76.2	5b	23.20		45.02	1.44	32.55	0.00	0.30	0.38	0.01	1.78	0.00	2.19	0.42	10.55	94.64
440NQ-34-76.2	76.2	5b	23.20		45.31	1.47	32.98	0.00	0.21	0.28	0.00	1.91	0.00	2.15	0.52	10.69	95.50
440NQ-34-76.2	76.2	5b	23.20		45.45	1.49	32.85	0.01	0.32	0.29	0.01	1.82	0.00	2.08	0.50	10.63	95.4 <b>4</b>
440NQ-34-76.2	76.2	5b	23.20		45.76	1.35	33.21	0.04	0.18	0.32	0.00	1.88	0.01	2.00	0.56	10.67	95.98
440NQ-34-76.2	76.2	5b	23.20		48.20	0.39	28.98	0.00	0.15	0.46	0.00	3.51	0.00	1.56	0.15	11.30	94.70
440NQ-34-76.2	76.2	5b	23.20		45.58	1.44	33.18	0.03	0.21	0.35	0.00	1.78	0.00	2.00	0.48	10.60	<b>95.64</b>
440NQ-34-76.2	76.2	5b	23.20		45.48	1.46	33.38	0.00	0.28	0.35	0.04	1.78	0.00	2.05	0.47	10.66	95.95
440NQ-34-76.2	76.2	5b	23.20	core	44.68	1.41	32.23	0.01	0.47	0.37	0.00	1.85	0.00	1.97	0.37	10.82	94.19
440NQ-34-76.2	76.2	5b	23.20	rim	45.06	1.46	32.46	0.01	0.34	0.35	0.00	1.83	0.00	1.97	0.45	10.72	94.64
440NQ-34-76.2	76.2	5b	23.20		45.21	1.52	32.36	0.00	0.48	0.36	0.00	1.75	0.01	2.14	0.41	10.93	95.17

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Muscovite 2

m	Unit	Au int. ppm	Comments	SiO2 %	TiO2 %	Al2O3 %	Cr2O3 %	V2O3 %
76.2	5b	23.20		45.87	1.14	32.15	0.03	0.23
76.2	5b	23.20		45.40	1.49	33.31	0.01	0.13
76 2	55	22.20		47 09	0 66	20.22	0.01	0 12

440NQ-34-76.2	76.2	5b	23.20		45.87	1.14	32.15	0.03	0.23	0.41	0.03	2.03	0.00	1.75	0.19	11.17	95.01
440NQ-34-76.2	76.2	5b	23.20		45.40	1.49	33.31	0.01	0.13	0.34	0.00	1.82	0.00	1.96	0.59	10.59	95.63
440NQ-34-76.2	76.2	5b	23.20		47.98	0.66	29.22	0.01	0.12	0.32	0.03	3.36	0.01	1.27	0.11	11.48	94.57
440NQ-34-76.2	76.2	5b	23.20		45.07	1.30	32.92	0.00	0.20	0.34	0.03	1.93	0.01	2.11	0.53	10.67	95.11
440NQ-34-77.5	77.5	5d	2.58		46.12	1.47	31.79	0.04	1.12	0.30	0.03	2.05	0.00	1.17	0.43	11.08	95.59
440NQ-34-77.5	77.5	5d	2.58		44.97	1.48	31.77	0.05	1.08	0.30	0.06	1.99	0.00	1.37	0.41	11.08	94.56
440NQ-34-77.5	77.5	5d	2.58		46.42	1.47	32.0 <del>9</del>	0.01	1.27	0.32	0.01	2.09	0.01	1.42	0.41	10.96	96.46
440NQ-34-77.5	77.5	5d	2.58		45.76	1.44	32.08	0.04	1.04	0.32	0.01	1.96	0.01	1.18	0.36	11.03	95.21
440NQ-34-77.5	77.5	5d	2.58		46.89	1.49	31.78	0.00	0.99	0.25	0.00	2.16	0.02	0.99	0.41	11.21	96.19
440NQ-34-77.5	77.5	5d	2.58		45.88	1.55	31.82	0.00	1.10	0.27	0.00	2.09	0.03	1.20	0.44	11.12	95.48
440NQ-34-77.5	77.5	5d	2.58		46.06	1.53	32.02	0.02	0.98	0.33	0.00	1.93	0.00	1.28	0.38	10.95	95.48
440NQ-34-77.5	77.5	5d	2.58		46.40	1.36	32.03	0.03	0.99	0.34	0.00	2.01	0.02	1.27	0.43	11.02	95.89
440NQ-34-79.1	79.1	5b	3.56		45.40	0.47	34.74	0.05	0.05	0.35	0.00	1.19	0.00	1.54	0.50	11.05	95.34
440NQ-34-79.1	79.1	5b	3.56		45.54	0.52	34.82	0.00	0.04	0.39	0.00	1.15	0.00	1.44	0.52	10.95	95.36
440NQ-34-79.1	79.1	5b	3.56		45.96	0.48	34.78	0.00	0.06	0.32	0.01	1.15	0.00	1.31	0.51	10.87	95.44
440NQ-34-79.1	79.1	5b	3.56		45.19	0.48	34.54	0.00	0.00	0.36	0.04	1.17	0.00	1.34	0.51	11.00	94.62
440NQ-34-79.1	79.1	5b	3.56		45.60	0.57	34.83	0.00	0.03	0.35	0.02	1.12	0.00	1.33	0.46	11.18	95.48
440NQ-34-79.1	79.1	5b	3.56		45.21	0.59	35.10	0.00	0.00	0.38	0.00	1.00	0.00	1.35	0.49	11.02	95.14
440NQ-34-79.1	79.1	5b	3.56		45.39	0.54	34.76	0.00	0.05	0.38	0.01	1.15	0.00	1.31	0.51	11.05	95.14
440NQ-34-79.1	79.1	5b	3.56	core	45.74	0.53	34.95	0.03	0.03	0.36	0.00	1.15	0.01	1.38	0.49	11.09	95.77
440NQ-34-79.1	79.1	5b	3.56	rim	45.31	0.45	34.75	0.00	0.03	0.34	0.00	1.09	0.00	1.32	0.48	11.01	94.78
440NQ-34-80.8	80.8	5b	11.50		42.87	0.61	30,93	0.00	3.13	1.44	0.00	1.56	0.04	5.57	0.39	9.34	95.87
440NQ-34-80.8	80.8	5b	11.50		42.29	0.95	30.54	0.08	3.48	1.39	0.00	1.49	0.04	5.96	0.39	9.07	95.69
440NQ-34-80.8	80.8	5b	11.50		41.17	1.39	26.67	0.07	6.41	1.56	0.01	2.19	0.00	6.61	0.39	8.61	95.09
440NQ-34-80.8	80.8	5b	11.50		43.40	0.57	30.71	0.02	2.95	1.32	0.00	1.61	0.01	4.91	0.31	9.66	95.46
440NQ-34-80.8	80.8	5b	11.50		42.75	1.21	26.98	0.03	6.52	1.65	0.05	2.02	0.00	4.43	0.32	9.59	95.57
440NQ-34-80.8	80.8	5b	11.50		41.17	1.33	27.07	0.04	6.03	1.52	0.02	2.05	0.00	6.66	0.35	8.80	95.03
440NQ-34-80.8	80.8	5b	11.50		41.54	1.37	27.71	0.25	5.56	1.58	0.00	2.16	0.01	6.44	0.39	8.83	<b>95.84</b>
440NQ-34-80.8	80.8	5b	11.50		41.00	1.43	27.92	0.21	5.25	1.56	0.01	2.02	0.00	6.28	0.40	8.80	94.87
440NQ-34-80.8	80.8	5b	11.50		41.22	1.42	27.47	0.24	5.57	1.49	0.02	2.14	0.04	6.50	0.41	8.64	95.16
440NQ-34-80.8	80.8	5b	11.50		41.31	1.30	28.30	0.06	5.12	1.54	0.03	2.01	0.00	5.61	0.39	9.19	94.86
440NQ-34-80.8	80.8	5b	11.50		41.04	1.54	28.27	0.06	5.45	1.60	0.00	1.92	0.03	6.08	0.41	8.90	95. <b>2</b> 9
440NQ-34-80.8	80.8	5b	11.50		40.70	1.39	27.89	0.07	5.73	1.55	0.01	2.01	0.00	6.33	0.36	8.82	94.85
440NQ-34-84.8	84.8	3a	6.00	core	45.07	0.76	33.48	0.00	0.02	0.52	0.02	1.73	0.02	4.01	0.52	9.77	95.91

MnO MgO % %

CaO

%

FeO

%

١

Total

%

K20

%

BaO Na2O

%

%

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Sample

Sample	m	Unit	Au int. ppm	Comments	SiO2 %	TiO2 %	AI2O3 %	Cr2O3 %	V2O3 %	FeO %	MnO %	MgO %	CaO %	BaO %	Na2O %	K2O %	Total %
440NQ-34-84.8	84.8	3a	6.00	rim	45.45	1.19	32.93	0.03	0.02	0.53	0.00	1.66	0.04	1.62	0.50	10.83	94.81
440NQ-34-84.8	84.8	3a	6.00	core	45.03	0.66	33.90	0.00	0.01	0.46	0.02	1.68	0.00	3.81	0.51	10.07	96.14
440NQ-34-84.8	84.8	3a	6.00	rim	45.73	1.26	33.03	0.00	0.03	0.46	0.00	1.70	0.00	1.44	0.51	10.87	95.03
440NQ-34-84.8	84.8	3a	6.00		45.26	0.67	33.78	0.01	0.04	0.44	0.01	1.66	0.01	2.18	0.45	10.83	95.33
440NQ-34-84.8	84.8	3a	6.00	core	45.01	1.30	32.53	0.04	0.00	0.61	0.00	1.90	0.00	3.66	0.46	10.22	95.74
440NQ-34-84.8	84.8	3a	6.00	rim	45.45	1.04	32.73	0.02	0.05	0.65	0.02	1.84	0.01	2.49	0.42	10.60	95.33
440NQ-34-84.8	84.8	3a	6.00		45.77	1.18	32.47	0.00	0.13	0.73	0.02	1.85	0.03	2.24	0.39	10.87	95.68
440NQ-34-84.8	84.8	3a	6.00		44.91	0.84	32.83	0.00	0.05	0.59	0.00	1.94	0.02	3.88	0.42	10.16	95.62
440NQ-34-84.8	84.8	3a	6.00		<b>46</b> .01	0.86	30.98	0.00	0.03	0.95	0.02	2.57	0.03	2.66	0.30	10.68	95.09
440NQ-34-85.3	85.3	5d	38.80		43.15	1.57	30.86	0.04	3.06	0.28	0.00	2.10	0.01	6.59	0.47	8.80	96.92
440NQ-34-85.3	85.3	5d	38.80		42.37	1.34	30.97	0.05	3.42	0.35	0.00	1.92	0.03	6.29	0.36	9.03	96.13
440NQ-34-85.3	85.3	5d	38.80		43.87	1.17	29.80	0.06	3.47	0.27	0.01	2.24	0.01	4.18	0.38	9.71	95.17
440NQ-34-85.3	85.3	5d	38.80		42.13	1.48	30.57	0.06	3.48	0.33	0.04	1.91	0.00	6.42	0.42	8.92	95.74
440NQ-34-85.3	85.3	5d	38.80		43.80	0.72	32.90	0.03	1.14	0.40	0.01	1.97	0.00	3.71	0.45	10.26	95.38
440NQ-34-85.3	85.3	5d	38.80		45.08	0.55	33.98	0.00	0.56	0.39	0.03	2.03	0.00	3.64	0.45	10.23	96.94
440NQ-34-85.3	85.3	5d	38.80		<b>44.77</b>	0.80	32.41	0.00	0.74	0.34	0.03	2.27	0.03	4.72	0.40	9.81	96.33
440NQ-34-86.3	86.3	5d	34.70		43.24	1.16	32.15	0.00	1.73	0.52	0.04	2.05	0.00	5.12	0.46	9.66	96.13
440NQ-34-86.3	86.3	5d	34.70		44.01	0.94	32.61	0.01	0.74	0.44	0.00	2.10	0.00	4.87	0.50	9.54	95.75
440NQ-34-86.3	86.3	5d	34.70		41.69	1.45	32.08	0.02	2.60	0.49	0.02	1.86	0.02	7.35	0.49	8.64	96.71
440NQ-34-86.3	86.3	5d	34.70		41.71	1.53	31.63	0.00	2.52	0.52	0.00	1.98	0.00	7.03	0.43	8.64	95.97
440NQ-34-86.3	86.3	5d	34.70		41.61	1.61	32.22	0.00	1.90	0.48	0.02	1.96	0.00	7.58	0.49	8.54	96.41
440NQ-34-86.3	86.3	5d	34.70		43.85	1.05	32.13	0.00	0.74	0.42	0.03	2.17	0.01	4.51	0.46	9.68	95.03
440NQ-34-86.3	86.3	5d	34.70		41.69	1.46	32.05	0.00	2.00	0.42	0.03	1.95	0.00	6.89	0.54	8.70	95.71
440NQ-34-86.3	86.3	5d	34.70		41.59	1.02	29.64	0.00	4.20	0.57	0.00	2.14	0.03	6.46	0.35	8.77	94.76
440NQ-34-86.3	86.3	5d	34.70		43.15	0.83	29.99	0.01	3.39	0.52	0.03	2.14	0.00	4.62	0.30	9.56	94.53
440NQ-34-86.9	86.9	7e	12.30		45.77	0.67	36.52	0.00	0.02	0.52	0.00	0.20	0.00	0.66	1.55	8.43	94.33
440NQ-34-86.9	86.9	7e	12.30		45.40	0.89	36.13	0.00	0.06	0.61	0.00	0.24	0.00	0.55	1.21	10.06	95.15
440NQ-34-86.9	86.9	7e	12.30		44.76	0.74	35.89	0.02	0.06	0.63	0.00	0.25	0.00	0.91	1.22	9.91	94.37
440NQ-34-86.9	86.9	7e	12.30		44.32	0.76	35.62	0.01	0.04	0.59	0.00	0.29	0.01	0.84	1.22	9.65	93.35
440NQ-34-86.9	86.9	7e	12.30		45.17	0.90	36.07	0.00	0.07	0.50	0.00	0.31	0.01	0.77	1.31	9.49	94.59
440NQ-34-86.9	86.9	7e	12.30		44.49	0.84	36.08	0.00	0.07	0.62	0.02	0.30	0.01	0.74	1.16	10.07	94.39
440NQ-34-86.9	86.9	7e	12.30		44.74	0.63	36.23	0.00	0.03	0.62	0.00	0.30	0.00	0.70	1.21	9.93	94.38
440NQ-34-86.9	86.9	7e	12.30		45.07	0.59	35.96	0.01	0.04	0.48	0.00	0.32	0.01	0.56	1.30	9.83	94.17
440NQ-34-86.9	86.9	7e	12.30		44.92	0.21	36.83	0.01	0.01	0.43	0.00	0.22	0.02	0.46	1.46	9.60	94.17

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Sample	m	Unit	Au int.	Comments	SiO2	TiO2	AI2O3	Cr2O3	V2O3	FeO	MnO	MgO	CaO	BaO	Na2O	K20	Total
			ppm		%	%	%	%	%	%	%	%	%	%	%	%	%
440NQ-34-88.4	88.4	7e	2.35		46.42	0.86	34.35	0.00	0.05	0.64	0.04	1.41	0.01	1.16	0.52	10.91	96.36
440NQ-34-88.4	88.4	7e	2.35		46.17	1.09	33.97	0.01	0.06	0.74	0.00	1.46	0.00	1.08	0.55	10.97	96.10
440NQ-34-88.4	88.4	7e	2.35		45.59	1.20	33.95	0.01	0.00	0.67	0.04	1.33	0.01	1.22	0.55	10.86	95.44
440NQ-34-88.4	88.4	7e	2.35		45.76	1.12	33.81	0.03	0.05	0.75	0.00	1.42	0.01	1.11	0.52	11.02	95.60
440NQ-34-88.4	88.4	7e	2.35		45.99	1.26	33.71	0.00	0.05	0.75	0.00	1.41	0.00	0.96	0.51	11.03	95.66
440NQ-34-88.4	88.4	7e	2.35		45.98	1.33	33.81	0.01	0.01	0.71	0.00	1.36	0.00	0.96	0.51	11.05	95.72
440NQ-34-88.4	88.4	7e	2.35		46.04	1.33	34.07	0.06	0.05	0.74	0.04	1.33	0.01	1.01	0.53	10.90	96.11
440NQ-34-88.4	88.4	7e	2.35		45.78	1.21	33.45	0.00	0.08	0.69	0.03	1.48	0.00	0.85	0.47	11.06	95.09
440NQ-34-88.4	88.4	7e	2.35		45.30	1.35	33.90	0.07	0.01	0.65	0.06	1.34	0.00	0.99	0.54	11.01	95.21
440NQ-34-88.4	88.4	7e	2.35		45.83	1.14	34.01	0.01	0.02	0.67	0.02	1.31	0.01	1.00	0.52	11.11	95.64
440NQ-34-90.9	90.9	7e	1.00		46.07	0.87	34.66	0.02	0.17	0.60	0.04	1.23	0.01	1.36	1.11	9.96	96.07
440NQ-34-90.9	90.9	7e	1.00		45.92	0.96	34.74	0.04	0.15	0.57	0.00	1.19	0.02	1.56	1.06	10.01	96.22
440NQ-34-90.9	90.9	7e	1.00		45.05	0.59	34.56	0.01	0.26	0.53	0.03	1.37	0.01	1.97	0.83	10.07	95.28
440NQ-34-90.9	90.9	7e	1.00		45.84	0.57	34.63	0.08	0.08	0.59	0.00	1.32	0.01	1.41	1.00	10.10	95.65
440NQ-34-94.2	94.2	7e	0.02		44.90	0.54	34.58	0.05	0.04	1.52	0.02	0.59	0.02	1.17	1.18	9.92	94.52
440NQ-34-94.2	94.2	7e	0.02		44.68	0.92	34.14	0.05	0.03	1.39	0.01	0.73	0.04	1.23	1.22	9.89	94.32
440NQ-34-94.2	94.2	7e	0.02		45.05	0.90	34.32	0.05	0.07	1.36	0.00	0.76	0.00	1.17	1.19	9.77	94.65
440NQ-34-94.2	94.2	7e	0.02		45.03	0.75	34.40	0.04	0.06	1.41	0.00	0.54	0.00	0.79	1.34	9.49	93.85
440NQ-34-94.2	94.2	7e	0.02		45.56	0.74	35.11	0.01	0.01	1.15	0.03	0.52	0.02	0.90	1.29	9.74	95.07
440NQ-34-94.2	94.2	7e	0.02		45.14	0.92	34.45	0.05	0.03	1.27	0.00	0.66	0.00	1.09	1.12	9.90	94.62
440NQ-34-94.2	94.2	7e	0.02		45.13	0.89	34.63	0.02	0.01	1.23	0.01	0.65	0.02	1.08	1.15	9.84	94.65
440NQ-34-94.2	94.2	7e	0.02		45.10	0.85	34.61	0.05	0.06	1.31	0.00	0.67	0.00	1.13	1.06	9.98	94.83

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Sample	m	Unit	Au int. ppm	Comments	SiO2 %	TiO2 %	AI2O3 %	Cr2O3 %	V2O3 %	FeO %	MnO %	MgO %	CaO %	BaO %	Na2O %	K2O %	Total %
47-5W-01		3a	0.10	core	45.99	0.62	36.28	0.00	0.00	0.22	0.01	0.43	0.01	0.24	0.70	10.42	94.93
47-5W-01		3a	0.10	rim	46.44	0.61	36.22	0.00	0.02	0.22	0.00	0.42	0.00	0.25	0.71	11.26	96.14
47-5W-01		3a	0.10		46.14	0.48	36.27	0.00	0.03	0.28	0.01	0.50	0.00	0.24	0.66	11.35	<b>95.96</b>
47-5W-01		3a	0.10		46.63	0.51	36.65	0.02	0.01	0.22	0.01	0.42	0.01	0.28	0.72	11.07	96.55
47-5W-01		3a	0.10	rim	45.45	0.52	36.23	0.00	0.01	0.24	0.02	0.41	0.00	0.30	0.57	11.54	95.28
47-5W-01		3a	0.10	core	46.10	0.55	35.91	0.00	0.00	0.26	0.01	0.52	0.00	0.21	0.67	11.16	95.38
47-5W-01		3a	0.10		46.14	0.56	35.76	0.01	0.01	0.25	0.02	0.52	0.00	0.30	0.46	11.55	95.55
47-5W-01		3a	0.10		45.94	0.54	36.08	0.05	0.00	0.26	0.00	0.49	0.00	0.26	0.69	11.14	95.45
47-5W-02		5d	1.08	core	47.19	1.44	32.49	0.01	0.32	0.34	0.01	1.57	0.00	0.31	0.38	11.70	<b>95</b> .75
47-5W-02		5d	1.08	rim	46.51	1.37	33.17	0.04	0.21	0.28	0.02	1.34	0.00	0.42	0.38	11.58	95.31
47-5W-02		5d	1.08		46.69	1.36	33.37	0.04	0.39	0.29	0.00	1.38	0.00	0.50	0.32	11.54	95.88
47-5W-02		5d	1.08		46.79	1.42	33.50	0.03	0.25	0.25	0.02	1.41	0.00	0.53	0.30	11.54	96.05
47-5W-02		5d	1.08		46.37	1.20	33.81	0.06	0.28	0.30	0.01	1.40	0.01	0.51	0.41	11.29	95.64
47-5W-02		5d	1.08		46.70	1.36	33.62	0.05	0.27	0.31	0.03	1.42	0.02	0.55	0.42	11.32	96.07
47-5W-03		3a	0.98		46.73	0.54	34.30	0.00	0.04	0.38	0.06	1.22	0.00	0.50	0.51	11.60	95.86
47-5W-03		3a	0.98		46.81	0.51	34.24	0.00	0.06	0.35	0.00	1.27	0.00	0.56	0.45	11.29	95.53
47-5W-03		3a	0.98	core	46.79	0.61	34.62	0.01	0.00	0.37	0.02	1.20	0.01	0.61	0.38	11.57	96.19
47-5W-03		3a	0.98	rim	46.16	0.46	34.16	0.00	0.01	0.40	0.00	1.19	0.00	0.62	0.46	11.45	94.91
47-5W-03		3a	0.98	core	46.81	0.52	34.09	0.02	0.00	0.37	0.00	1.30	0.00	0.59	0.47	11.36	95.52
47-5W-03		3a	0.98	rim	46.38	0.53	34.53	0.00	0.02	0.39	0.01	1.17	0.00	0.54	0.45	11.52	95.53
47-5W-03		3a	0.98		45.87	0.59	34.59	0.00	0.02	0.40	0.00	1.15	0.00	0.55	0.48	11.34	94.98
47-5W-03		3a	0.98		<b>46.76</b>	0.59	34.59	0.01	0.00	0.34	0.00	1.20	0.00	0.52	0.48	11. <b>49</b>	95.98
47-5W-03		3a	0.98		46.13	0.54	34.32	0.01	0.03	0.37	0.02	1.18	0.00	0.55	0.48	11.44	95.06
47-5W-03		3a	0.98		46.79	0.55	34.25	0.02	0.01	0.37	0.00	1.32	0.01	0.51	0.46	11.62	95.90
47-5W-04		5j	0.42		48.08	0.32	28.49	0.03	0.34	1.97	0.00	3.35	0.00	0.63	0.12	11.79	95.14
47-5W-04		5j	0.42		47.72	0.84	26.24	0.12	1.54	2.01	0.00	3.90	0.02	0.72	0.12	11.70	94.91
47-5W-04		5j	0.42		48.73	0.79	26.39	0.19	0.86	1.94	0.00	3.67	0.01	0.87	0.11	11.81	95.35
47-5W-04		5j	0.42		48.25	0.46	28.52	0.05	0.56	1.49	0.04	3.10	0.04	0.73	0.12	11.63	94.99
47-5W-08B		5a	0.92		47.76	0.88	28.40	0.00	0.77	0.90	0.02	3.17	0.00	0.68	0.09	11.79	94.45
47-5W-08B		5a	0.92		47.70	0.73	29.54	0.01	0.93	0.87	0.00	2.77	0.02	0.68	0.14	11.71	95.09
47-5W-08B		5а	0.92		47.95	0.65	28.10	0.06	0.73	1.03	0.00	3.39	0.00	0.58	0.09	11.75	<b>94</b> .33
47-5W-08B		5a	0.92		45.98	1.47	28.88	0.06	2.60	0.70	0.05	2.41	0.00	0.74	0.27	11.43	94.58
47-5W-08B		5a	0.92		46.18	1.45	29.14	0.02	2.78	0.71	0.01	2.29	0.00	0.78	0.28	11.40	95.05
47-5W-08B		5a	0.92		46.26	1.03	28.90	0.18	2.55	0.74	0.02	2.59	0.00	0.56	0.29	11.37	94.49
47-5W-08B		5a	0.92		47.87	0.59	27.89	0.15	0.49	1.00	0.01	3.65	0.00	0.49	0.18	11.72	94.03
47-5W-08B		5a	0.92		47.42	0.35	28.69	0.00	0.60	1.28	0.00	3.84	0.00	0.44	0.13	11.83	94.58

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Comments	SiO2 %	TiO2 %	AI2O3 %	Cr2O3 %	V2O3 %	FeO %	MnO %	MgO %	CaO %	BaO %	Na2O %	K2O %
	46.34	0.27	31.84	0.00	0.09	1.31	0.00	2.10	0.00	0.57	0.25	11.64
	45.94	0.64	31.50	0.00	0.12	1.40	0.02	2.09	0.00	0.64	0.23	11.30

Total

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460-109-45.7	45.7	10a	180.90		46.34	0.27	31.84	0.00	0.09	1.31	0.00	2.10	0.00	0.57	0.25	11.64	94.41
460-109-45.7	45.7	10a	180.90		45.94	0.64	31.50	0.00	0.12	1.40	0.02	2.09	0.00	0.64	0.23	11.30	93.86
460-109-45.7	45.7	10a	180.90		47.22	0.30	31.11	0.03	0.20	1.49	0.04	2.61	0.00	0.63	0.19	11.56	95.37
460-109-45.7	45.7	10a	180.90		47.75	0.38	31.38	0.09	0.30	1.48	0.00	2.69	0.01	0.63	0.17	11.53	96.42
460-109-45.7	45.7	10a	180.90		46.55	0.63	31.14	0.00	0.70	1.50	0.05	3.01	0.00	0.42	0.19	11.77	95.94
460-109-45.7	45.7	10a	180.90	intergrown w Au	47.20	0.43	29.77	0.11	0.97	1.56	0.00	2.70	0.04	0.72	0.20	11.50	95.20
460-109-45.7	45.7	10a	180.90	intergrown w Au	47.92	0.14	28.77	0.06	0.32	1.68	0.02	3.59	0.02	0.83	0.13	11.38	94.86
460-109-45.7	45.7	10a	180.90	-	46.58	0.24	31.44	0.00	0.93	1.54	0.02	2.33	0.00	0.60	0.22	11.59	95.49
440NQ-34-86.9	86.9	7e	12.30	late sericite	51.35	0.00	36.98	0.04	0.00	0.01	0.00	0.01	0.21	0.05	3.62	3.28	95.54
440NQ-34-86.9	86.9	7e	12.30	late sericite	50.89	0.03	37.04	0.00	0.04	0.01	0.02	0.04	0.64	0.05	4.37	1.09	94.22
440NQ-34-86.9	86.9	7e	12.30	late sericite	48.96	0.00	37.50	0.00	0.00	0.00	0.00	0.02	0.24	0.02	2.97	5.34	95.05
440NQ-34-94.2	94.2	7e	0.02	late sericite	46.29	0.02	34.60	0.00	0.01	1.64	0.01	0.02	0.04	0.12	0.15	11.61	94.49
440NQ-34-94.2	94.2	7e	0.02	late sericite	46.65	0.00	37.53	0.00	0.02	0.43	0.00	0.04	0.04	0.21	0.40	11.18	96.49
440NQ-34-94.2	94.2	7e	0.02	late sericite	46.26	0.05	35.44	0.02	0.01	1.23	0.00	0.01	0.01	0.12	0.12	11.75	95.01

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Sample

m Unit Au int.

ppm

### Hemlo Tourmaline Probe Data

#### Unpublished data from J.R. Clark

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 20 nA; 20 s peak counts, except 35 s for V, and 45 s for Ba; 5 um beam; high-precision quantitative data Total Fe as FeO unless noted. Lower detection limits at 2SD are 0.01-0.03 wt %, except 0.04 wt% for BaO.

Diopside-, garnet, orthoclase, albite-based standards for all major elements.

									Weight I	Percent						
Sample	m	Unit	Au int. ppm	Comments	SiO2 %	TiO2 %	AI2O3 %	V2O3 %	FeO %	MnO %	MgO %	CaO %	BaO %	Na2O %	K2O %	Total %
47-5W-08b		5a	0.92	porph	37.46	0.45	31.46	1.31	1.29	0.01	9.98	0.27	0.01	2.42	0.09	84.75
47-5W-08b		5a	0.92	porph	37.51	0.40	31.97	0.91	1.30	0.04	9.57	0.16	0.05	2.48	0.08	84.47
47-5W-08b		5a	0.92	porph	37.37	0.43	31.46	1.24	1.23	0.04	9.90	0.17	0.00	2.42	0.09	84.34
47-5W-08b		5a	0.92	porph	37.24	0.44	31.58	1.06	1.22	0.07	9.82	0.17	0.00	2.41	0.09	84.10
440NQ-34-11.1	11.1	5b	5.00	rextal detrit	36.95	0.36	32.66	0.11	1.19	0.03	9.92	0.93		2.06	0.03	84.25
440NQ-34-11.1	11.1	5b	5.00	rextal detrit	36.70	0.43	32.60	0.11	1.13	0.04	9.84	0.84		2.15	0.05	83.88
440NQ-34-11.1 440NQ-34-11.1 440NQ-34-11.1	11.1 11.1 11.1	5b 5b 5b	5.00 5.00 5.00	rextal detrit rextal detrit rextal detrit	37.30 37.12 37.26	0.31 0.41 0.40	32.67 32.43 32.39	0.17 0.23 0.22	0.49 0.35 0.39	0.02 0.04 0.01	10.26 10.33 10.48	0.66 0.67 0.58		2.28 2.35 2.40	0.06	84.22 83.97 84.20
440NQ-34-11.1	11.1	55	5.00	rextal detrit	37.33	0.32	32,50	0.22	0.42	0.02	10.42	0.61		2.29	0.06	84.19
440NQ-34-11.1	11.1	55	5.00	rextal detrit	37.56	0.27	32,37	0.07	0.40	0.03	10.37	0.59		2.30	0.03	83.98
440NQ-34-50.2	50.2	4c	0.03	porph	36.48	0.46	29,92	0.05	4.00	0.03	9.69	1.49		1.95	0.05	84.12
440NQ-34-50.2	50.2	4c	0.03	porph	36.78	0.22	29.97	0.17	5.17	0.09	8.50	0.23		2.54	0.03	83.70
440NQ-34-50.2	50.2	4c	0.03	porph	35.74	0.63	30.41	0.23	4.57	0.08	8.91	1.61		1.82	0.08	84.07
440NQ-34-50.2	50.2	4c	0.03	porph	36.00	0.54	30.33	0.35	4.04	0.07	9.17	1.54		1.88	0.06	83.97
440NQ-34-50.2	50.2	4c	0.03	porph	36.02	0.57	30.37	0.25	4.43	0.07	9.11	1.56	0.02	1.87	0.08	84.33
440NQ-34-79.1	79.1	5b	3.56	porph	37.33	0.23	34.45	0.00	1.28	0.03	8.88	0.46		2.02	0.06	84.75
440NQ-34-79.1	79.1	5b	3.56	porph	37.28	0.23	34.24	0.01	1.37	0.01	8.86	0.48		1.99	0.08	84.54
440NQ-34-79.1 440NQ-34-79.1	79.1 79.1	5b 5b	3.56 3.56	porph porph	37.19 37.39	0.34 0.17	33.76 34.20	0.00	1.45 0.88	0.00	8.99 9.10	0.48 0.35	0.02	2.11 1.83	0.08	84.40 84.02

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Sample	m	Unit	Au int.	Comments	SiO2	TiO2	A12O3	V2O3	FeO	MnO	MgO %	CaO %	BaO «	Na2O %	K2O %	Total %
			ppm		70	70	70	/0	70	70	70	/0	70	10	70	70
440NQ-34-85.3	85.3	5d	38.80	rextal detrit	37.77	0.09	32.83	0.00	0.29	0.00	10.20	0.19		2.01	0.02	83.40
440NQ-34-85.3	85.3	5d	38.80	rextal detrit	37.81	0.19	32.41	0.05	0.42	0.02	10.58	0.33		2.32	0.04	84,16
440NQ-34-85.3	85.3	5d	38.80	rextal detrit	37.48	0.24	32.81	0.03	0.31	0.00	10.33	0.47		2.41	0.03	84.11
440NQ-34-85.3	85.3	5d	38.80	rextal detrit; core	37.96	0.10	33.58	0.03	0.33	0.01	9.68	0.18		2.32	0.03	84.23
440NQ-34-85.3	85.3	5d	38.80	rextal detrit; rim	36.80	0.44	31.73	0.32	0.61	0.00	10.74	1.66		1.70	0.05	84.05
440NQ-34-86.3	86.3	5d	34.70	rextal detrit	36.61	0.33	31.05	2.08	0.89	0.05	10.19	1.56	0.03	1.61	0.05	84.44
440NQ-34-86.3	86.3	5d	34.70	rextal detrit	36.64	0.32	31.41	1.45	0.52	0.02	10.23	1.20	0.00	1.78	0.04	83.60
440NQ-34-86.3	86.3	5d	34.70	rextal detrit	36.73	0.43	30.51	1.07	0.71	0.01	11.25	2.25	0.00	1.42	0.06	84.43
440NQ-34-86.3	86.3	5d	34.70	rextal detrit	36.71	0.39	30.93	1.89	0.86	0.02	10.24	1.35	0.00	1.71	0.05	84.17
440NQ-34-86.3	86.3	5d	34.70	rextal detrit	36.54	0.45	31.11	1.11	0.50	0.03	10.73	1.68	0.08	1.61	0.04	83.88
440NQ-34-88.4	88.4	7e	2.35	rextal detrit	36.95	0.52	32.52	0.02	1.89	0.00	9.55	1.34	0.03	1.66	0.06	84.54
440NQ-34-88.4	88.4	7e	2.35	rextal detrit	36.92	0.56	32.45	0.00	2.10	0.01	9.55	1.38	0.01	1.69	0.05	84.72
440NQ-34-88.4	88.4	7e	2.35	rextal detrit	37.04	0.51	32.99	0.04	2.03	0.01	9.80	1.37	0.05	1.73	0.06	85.63
440NQ-34-88.4	88.4	7e	2.35	rextal detrit	37.12	0.39	33.48	0.06	2.81	0.03	8.70	0.84	0.00	1.73	0.03	85.17
440NQ-34-88.4	88.4	7e	2.35	rextal detrit	36.76	0.53	33.04	0.07	2.07	0.04	9.23	1.29	0.00	1.66	0.05	84.73
440NQ-34-88.4	88.4	7e	2.35	rextal detrit	36.14	0.48	32.33	0.04	2.55	0.00	9.45	1.61	0.00	1.51	0.04	84.15
440NQ-34-88.4	88.4	7e	2.35	rextal detrit	36.71	0.47	31.71	0.02	2.99	0.06	9.72	1.37	0.00	1.68	0.03	84.77
440NQ-34-88.4	88.4	7e	2.35	rextal detrit	36.76	0.39	32.35	0.02	2.48	0.04	8.98	0.97	0.00	1.71	0.05	83.74
440NQ-34-90.9	90.9	7e	1.00	rextal detrit	37.19	0.29	31.66	0.13	0.85	0.02	10.98	1.35		1.88	0.03	84.38
440NQ-34-90.9	90.9	7e	1.00	rextal detrit	36.78	0.31	32.60	0.05	1.14	0.02	10.03	1.14		2.01	0.04	84.11
440NQ-34-90.9	90.9	7e	1.00	rextal detrit	37.13	0.31	32.48	0.12	0.87	0.02	10.83	1.30		1.95	0.03	85.02
440NQ-34-90.9	90.9	7e	1.00	rextal detrit	36.66	0.40	32.35	0.11	1.30	0.02	10.10	1.10		2.06	0.04	84.13

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# Hemlo Titanite Probe Data Unpublished data from J.R. Clark

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 30 nA; 20 s peak counts, except 45 s for V and F; 2 um beam; high-precision quan Total Fe as Fe2O3 unless noted. Lower detection limits at 2SD are 0.01-0.03 wt %.

Titanite-based standards for all major elements. V corrected for Ti interference.

			i inajor or						weight %	6						
Sample	m	Unit	Au int.	Comments	SiO2	TiO2	AI2O3	V2O3	Fe2O3	MnO	MgO	CaO	Na2O	F	O=F	Total
•			ppm		%	%	%	%	%	%	%	%	%	%	%	%
5-13-26.2	26.2	<b>5</b> i	24.800	core	30.19	30.68	1.73	5.38	0.17	0.03	0.00	28.09	0.00			96.27
5-13-26.2	26.2	5i	24.800	intermed	30.39	30.88	1.72	5,52	0.16	0.04	0,00	28.30	0.00			97.01
5-13-26.2	26.2	5i	24.800	rim	30.33	30.35	1.84	5.61	0.18	0.07	0.00	28.28	0.01			96,68
5-13-26.2	26.2	5i	24.800		30.37	28.34	1.47	7.59	0.18	0.03	0.00	28.37		0.10	-0.04	96.40
5-13-26.2	26.2	5i	24.800		30.10	28.13	1.51	8.27	0.16	0.06	0.00	28.16	0.00			96,38
5-13-26.2	26.2	5i	24.800		30.20	27.22	1.55	8,82	0.31	0.04	0.00	28.48		0.13	-0.06	96.69
5-13-26.2	26.2	5i	24.800		30.24	32.34	1.60	4.17	0.21	0.03	0.00	28.39	0.02			97.01
5-13-26.2	26.2	5i	24.800		30.32	33.80	1.59	2.99	0.32	0.03	0.00	28.36	0.00			97.42
5-13-26.2	26.2	5i	24.800		30.14	26.80	1.46	9.09	0.29	0.06	0.00	28.48	0.00	*		96.31
5-13-26.2	26.2	5i	24.800		30.33	28.04	1.63	8.03	0.24	0.04	0.00	28.36	0.00			96.67
440NQ-34-11.1	11.1	5b	5.000		30.64	37.34	2.05	0.23	0.04	0.01	0.01	28.50	0.02			98,83
440NQ-34-11.1	11.1	5b	5.000		30.76	37.15	2.04	0.23	0.04	0.02	0.01	28.44	0.01			98.71
440NQ-34-11.1	11.1	5b	5.000		30.72	35.56	2.99	0.28	0.11	0.03	0.00	28.56	0.00			98.24
440NQ-34-11.1	11.1	5b	5.000		31.26	36.15	3.01	0.25	0.03	0.01	0.04	27.94	0.01			98.70
440NQ-34-11.1	11.1	5b	5.000		31.02	34.86	3.44	0,80	0.15	0.03	0.63	26.95	0.14			98.02
440NQ-34-12.5	12.5	5d	3.780		30.75	37.45	0.96	1.44	0.01	0.01	0.00	28.21	0.00			98.83
440NQ-34-12.5	12.5	5d	3.780		30.97	38.34	0.40	1.22	0.14	0.00	0.00	28.19	0.00			99,26
440NQ-34-12.5	12.5	5d	3.780		31.02	36.15	1.06	1. <del>9</del> 3	80.0	0.02	0.00	27.95	0.01			98.21
440NQ-34-50.2	50.2	4c	0.033		30.98	35.40	3.07	0.26	0.41	0.06	0.01	28.92	0.00			99,12
440NQ-34-50.2	50.2	4c	0.033		31.28	35.44	3.31	0.16	0.39	0.17	0.00	28.89	0.01			99.65
440NQ-34-50.2	50.2	4c	0.033		30.92	36.56	2.37	0.25	0.44	0.16	0.00	28.81	0.02			99.53
440NQ-34-50.2	50.2	4c	0.033		31.07	35.79	3.23	0.42	0.41	0.23	0.01	28.51	0.01			99.67
440NQ-34-50.2	50.2	4c	0.033	core	30.49	36.15	2.39	0.23	0.53	0.12	0.12	28.58	0.00			98.60
440NQ-34-50.2	50.2	4c	0.033	rim	30.67	35.18	2.90	0.25	0.54	0.14	0.01	28.73	0.01			98.42

Titanite 1

Sample	m	Unit	Au int.	Comments	SiO2	TiO2	AI2O3	V2O3	Fe2O3	MnO	MgO	CaO	Na2O	F	O=F	Total
			ppm		%	%	%	%	%	%	%	%	%	%	%	%
440NQ-34-76.2	76.2	5b	23,200		31.05	38.93	1.69	0.33	0.06	0.02	0.00	28.67		0.29	-0.12	100.91
440NQ-34-76.2	76.2	5b	23.200		31.28	36.64	2.91	0.38	0.03	0.01	0.01	28.77		0.43	-0.18	100.27
440NQ-34-76.2	76.2	5b	23,200		31.34	38.09	1.57	0.53	0.08	0.00	0.00	29.03		0.19	-0.08	100.75
440NQ-34-76.2	76.2	5b	23.200		31.22	37.82	1.70	0.46	0.14	0.02	0.00	28.49		0.19	-0.08	99.97
440NQ-34-76.2	76.2	5b	23.200	core	30.69	37.54	1.57	0.23	0.05	0.02	0.00	28.61		0.17	-0.07	98.81
440NQ-34-76.2	76.2	5b	23.200	intermed	30.94	38.76	1.29	0.22	0.04	0.06	0.00	28.77		0.07	-0.03	100.12
440NQ-34-76.2	76.2	5b	23.200	rim	31.30	37.77	2.12	0.25	0.09	0.05	0.00	29.13		0.34	-0.14	100.92
440NQ-34-76.2	76.2	5b	23.200		31.24	38.42	1.62	0.32	0.05	0.04	0.00	28.98		0.27	-0.11	100.83
440NQ-34-77.5	77.5	5d	2.580		31.98	33.77	4.27	0.7 <del>9</del>	0.01	0.02	0.01	28.69		0.53	-0.22	99.85
440NQ-34-80.8	80.8	5b	11.500		30.58	32.26	1.64	4.57	0.23	0.07	0.00	28.79		0.29	-0.12	98.31
440NQ-34-80,8	80.8	5b	11,500		30.36	32.15	1.36	5.12	0.15	0.03	0.00	28.69		0.20	-0.09	97.96
440NQ-34-80.8	80.8	5b	11.500		30.19	31.20	1.66	5.19	0.20	0.02	0.00	28.88		0.30	-0.13	97.52
440NQ-34-80.8	80.8	5b	11.500		30.96	34.66	1.85	2.66	0.23	0.04	0.00	28.81		0.12	-0.05	99.28
440NQ-34-80.8	80.8	5b	11.500		30.62	33.70	1.86	3.10	0.18	0.02	0.00	28.84		0.19	-0.08	98.43
440NQ-34-80.8	80.8	5b	11.500		30.53	34.63	1.70	2.64	0.27	0.03	0.00	28.76		0.29	-0.12	98.73
440NQ-34-80.8	80.8	5b	11.500	core	30.86	34.39	1.59	3.19	0.19	0.04	0.00	28.66		0.23	-0.10	99.06
440NQ-34-80.8	80.8	5b	11.500	rim	31.12	36.01	2.03	1.31	0.19	0.04	0.00	28.65		0.31	-0.13	99.53
440NQ-34-84.8	84.8	Зa	6.000		30.53	38.60	1.22	0.10	0.17	0.05	0.00	28.78		0.10	-0.04	99.52
440NQ-34-84.8	84.8	3a	6.000		30.69	38.97	1.24	0.12	0.16	0.04	0.00	28.53		0.11	-0.04	99.81
440NQ-34-84.8	84.8	3a	6.000		30.34	38.05	1.46	0.12	0.18	0.06	0.00	28.61		0.16	-0.07	98.90
440NQ-34-84.8	84.8	3a	6.000		30.40	38.09	1.62	0.11	0.12	0.07	0.00	28.67		0.08	-0.03	99.12
440NQ-34-85.3	85.3	5d	38.800		30.65	35.45	2.52	0.79	0.06	0.04		28.91		0.26	-0.11	98.58
440NQ-34-85.3	85.3	5d	38.800		30.89	36.71	1.85	0.94	0.05	0.04		28.97		0.13	-0.05	99.52
440NQ-34-85.3	85.3	5d	38.800		30.56	35.22	2.38	0.96	0.05	0.02		28.58		0.17	-0.07	97.87
440NQ-34-86.3	86.3	5d	34.700	core	30.88	36.84	1.50	1.19	0.02	0.04		28.84		0.21	-0.09	99.44
440NQ-34-86.3	86.3	5d	34.700	intermed	30.88	37.11	1.42	0.94	0.05	0.01		28.74		0.17	-0.07	99.25
440NQ-34-86.3	86.3	5d	34.700	rim	31.01	35.77	1.84	1.18	0.07	0.05		28.53		0.30	-0.13	98.63
440NQ-34-86.3	86.3	5d	34.700		30.64	35.46	2.00	1.24	0.06	0.02		28.45		0.19	-0.08	97.98
460-109-45.7	45.7	10a	180.900	core	30.36	36.66	1.42	0.47	0.29	0.04		28.28		0.09	-0.04	97.57
460-109-45.7	45.7	10a	180.900	intermed	30.33	37.30	1.27	0.57	0.24	0.05		27.85		0.11	-0.05	97. <b>66</b>
460-109-45.7	45.7	10a	180.900	rim	30.35	37.40	1.29	0.67	0.29	0.05		27.87		0.17	-0.07	98.02
460-109-45.7	45.7	10a	180.900		30.48	37.66	1.22	0.53	0.30	0.07		28.15		0.12	-0.05	98.47
460-109-45.7	45.7	10a	180.900		30.77	37.47	1.33	0.53	0.23	0.08		28.74		0.14	-0.06	99.23
460-109-45.7	45.7	10a	180,900		30.51	35.87	1.25	1.82	0.20	0.09		28.23		0.12	-0.05	98.04

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Titanite 2

### Hemlo Pumpellyite(?) Probe Data

Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 30 nA; 20 s peak counts, except 45 s for V; 5 um beam. Total Fe as Fe2O3. Lower detection limits at 3-sigma are 0.02 wt% for SiO2, Al2O3, MgO and Na2O; 0.03 wt% for V2O3, MnO and CaO; 0.04 wt% for TiO2 and Fe2O3. Andradite-, pyrope- and vanadinite-based standards for major elements.

Samola	m	SiO	TIO	AL-O	V O	Ee O	MaQ	MaO	C2O	No.O	Total
Sample		%	%	%	%	₩ %	%	myO %	%	Nd <sub>2</sub> O %	*0tai %
GG-20	879.6	36.69	0.00	23.55	1.93	0.04	0.06	5.07	23.08	0.01	90.42
GG-20	879.6	37.41	0.03	23.63	0.95	0.58	0.10	5.54	23.03	0.00	91.27
GG-20	879.6	36.96	0.00	24.24	0.38	0.57	0.11	5.16	23.40	0.00	90.82
GG-20	879.6	35.37	0.00	18.22	7.64	1.29	0.03	4.37	22.17	0.01	89.09
GG-20	879.6	36.41	0.00	21.92	3.81	0.03	0.07	4.71	22.79	0.00	89.75
GG-20	879.6	36.91	0.00	22.61	1.65	0.48	0.06	5.56	23.16	0.01	90.43
GG-20	879.6	35.75	0.03	20.62	5.51	0.03	0.03	4.64	22.60	0.01	89.23
GG-20	879.6	36.63	0.00	22.64	2.85	0.74	0.07	4.87	22.99	0.02	90.80
GG-20	879.6	35.32	0.08	20.43	5.81	0.03	0.06	4.62	22.56	0.02	88.92
GG-20	879.6	36.50	0.03	22.58	2.75	1.07	0.05	4.69	23.08	0.01	90.75
GG-20	879.6	36.11	0.56	19.87	5.54	0.06	0.05	5.33	22,48	0.01	90.02
GG-20	879.6	36.13	0.11	20.12	5.92	0.77	0.06	4.73	22,49	0.01	90.34
GG-20	879.6	37.09	0.00	24.42	0.86	0.59	0.09	5.23	23.30	0.00	91.58
GG-20	879.6	35.95	0.05	20.15	6.54	0.47	0.07	4.47	22.42	0.00	90.13
GG-20	879.6	35.44	0.00	20.16	6.06	0.05	0.09	4.60	21.95	0.00	88.34
GG-20	879.6	36.27	0.02	22.68	2.69	0.92	0.06	4.50	22.35	0.01	89.49
GG-20	879.6	36.62	0.00	23.20	1.37	1.20	0.05	4.86	22.65	0.00	89.94

#### Weight Percent
## Hemlo Hydrogrossular? Probe Data

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Jeol JXA-8900L electron microprobe using ZAF correction; 15 kV, 30 nA; 20 s peak counts, except 45 s for V; 5 um beam.

Total Fe as Fe2O3. Lower detection limits at 3-sigma are 0.02 wt% for SiO2, MgO and Na2O; 0.03 wt% for Al2O3, V2O3 and CaO; 0.04 wt% for TiO2, Fe2O3 and MnO. Andradite-, pyrope- and vanadinite-based standards for major elements.

	• •		Weight Percent									
Sample	m	Comments	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	V <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	Totai
			%	%	%	%	%	%	%	%	%	%
GG-20	879.6		35.61	0.18	12.32	9.88	2.93	0.45	0.02	35.12	0.00	96.49
GG-20	879.6		35.66	0.36	11.11	11.62	2.09	0.39	0.03	34.98	0.00	96.24
GG-20	879.6	core	36.34	0.03	15.31	8.80	0.15	0.34	0.01	35.96	0.00	96.93
GG-20	879.6	rim	35.90	0.15	11.58	11.54	2.31	0.31	0.01	35.08	0.00	96.88
GG-20	879.6		36.26	0.05	12.76	12.24	0.11	0.27	0.01	35.51	0.00	97.20
GG-20	879.6		35.65	0.60	11.75	12.58	0.45	0.26	0.02	35.10	0.00	96.39
GG-20	879.6		35.55	0.55	12.26	12.02	0.15	0.31	0.05	35.44	0.01	96.33
GG-20	879.6		35.63	0.55	11.21	12.46	1.24	0.21	0.01	35.23	0.00	96.54
GG-20	879.6	core	36.13	0.13	11.92	12.72	0.38	0.30	0.01	35.39	0.00	96.98
GG-20	879.6	rim	36.49	0.28	8.22	15.17	2.72	0.47	0.01	34.30	0.00	97.67
GG-20	879.6		35.60	0.53	11.48	11.39	2.03	0.33	0.01	35.02	0.00	96.38
GG-20	879.6		35.47	0.26	10.58	12.77	1.84	0.26	0.00	34.58	0.00	95.76
GG-20	879.6		35.18	0.30	10.49	12.70	1.95	0.29	0.00	34.32	0.00	95.22
GG-20	879.6		35.44	0.14	10.56	13.18	1.68	0.26	0.01	34.45	0.00	95.73

## Appendix V

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Fluid inclusion data

## Hemlo fluid inclusion homogenization temperatures L = liquid, V = vapor, S = solid

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Sample	Inclusion type	Homogenization temperatures °C
430-16-33.6	LV	188.1
	LV	181.1
	LV	177.6
	LV	172.2
	LV	170.1
430-16-33.6	LVS (halite)	160.3
	LVS (halite)	155.1
	LVS (halite)	131.5
	LVS (halite)	174.2
	LVS (halite)	165.3
430-16-33.6	LV sulfide	194.3
	LV	152.2
	LV	191
	LV	195.4
	LV	184
430-16-33.6	LVS (halite)	150
	LVS (halite)	142
	LVS (halite)	141
	LVS (halite)	165
	LVS (halite)	169.5
430-16-33.6	LVS (halite)	167.2
	LVS (halite)	171.5
	LVS (halite)	141.5
	LVS (halite)	184.5
	LVS (halite)	164.5
430-16-33.6	LVSS (halite+elongate mineral)	136.5
	LVSS (halite+elongate mineral)	151.3
	LVSS (halite+elongate mineral)	123.3
	LVSS (halite+elongate mineral)	149.3
	LVSS (halite+elongate mineral)	123.3

Sample	Inclusion type	Homogenization temperatures		
		°C		
430-16-33.6	LV	132		
	LV	176.5		
	LV	178.1		
	LV	177.5		
	LV	182.5		
430-16-33.6	LVS (halite)	159.5		
	LVS (halite)	146.8		
	LVS (halite)	160.2		
	LVSS (halite+elongate mineral)	147.8		
430-16-33.6	LVS (halite)	152.5		
	LVS (halite)	151.8		
	LVS (halite)	150.8		
440NQ-34-85.3	LV	158.9		
	LV sulfide	183		
	LV sulfide	178.5		
	LV sulfide	186.6		
440NQ-34-85.3	LV	93.7		
	LV	168.8		
	LV	152.3		
	LV	191.7		
	LV	104		
440NQ-34-85.3	LV sulfide	154.9		
	LV	147.7		
	LV sulfide	136.6		
	LV	152.5		
440NQ-34-85.3	LV sulfide	159.5		
	LV sulfide	155.5		
	LV	131.1		
	LV	133		
440NQ-34-85.3	LV sulfide	125.5		
	LV sulfide	128.4		
	LV	137.1		
	LV	130.4		

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Sample		Inclusion type	Homogenization temperatures °C
440NQ-34-85.3	LV		207
	LV		273
	LV		275
	LV		294
440NQ-34-85.3	LV		151
	LV		162
	LV		341.2
440NQ-34-85.3	LV		301
	LV		117.5
440NQ-34-85.3	LV		154.1
	LV		147.2
	LV		145.5
	LV		150.1
	LV		135.8
440NQ-34-85.3	LV		156.1
	LV		161.5
	LV		139
	LV		157.4
	LV		148.5
440NQ-34-85.3	LV		133.4
	LV		134.5
	LV		150.2
440NQ-34-85.3	LV		150.3
	LV		176.7
	LV		145.6
	LV		177.8
	LV		178.1
440NQ-34-85.3	LV		129.6
	LV		194.3
	LV		193.8
	LV		162.1

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Fluid Inc. 3

Sample		Inclusion typ <del>e</del>	Homogenization temperatures °C
440NQ-34-85.3	LV		109
	LV		135
	LV		136
	LV		177.6
	LV		170.3
440NQ-34-85.3	LV		146.3
	LV		155.4
	LV		169.2
	LV		165.2
	LV		169.3
440NQ-34-85.3	LV		136.3
	LV		136.5
	LV		122.5

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