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Stratigraphic and Structural Setting of the Hemlo Gold Deposit, Ontario, Canada

SHOUFA LIN†,*

Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8, Canada

Abstract

Results of detailed surface and underground mapping and a compilation of data from the three gold mines in the Hemlo area, Ontario, are presented. In particular, the lithostratigraphy of the area is established, the nature of the lithologic units spatially closely associated with the ore and the protolith of the ore are determined, and the deformation history and the three-dimensional geometry of the area are elucidated. The genesis of the gold deposit is discussed in context of these results.

Four generations (G_1 to G_4) of ductile structures, as well as brittle faulting, are recognized. G_2 deformation is the strongest and the geometry of the Hemlo camp is dominated by macroscopic (camp-scale) "S"-shaped F_2 folds. The two ore zones at Hemlo, the main and lower ore zones, are spatially associated with the two limbs of a newly recognized camp-scale F_2 fold, the Moose Lake fold, and the orebody is folded by F_2 at outcrop scale, mine scale, and possibly camp scale. G_2 deformation is most intense in the Hemlo shear zone, interpreted to be a sinistral transpressional zone. The Hemlo gold deposit is hosted in the shear zone, mainly in the segment that trends east-southeasterly where deformation is stronger. The main gold mineralization at Hemlo occurred before G_2 or early during G_2 deformation and before peak metamorphism. The latter took place during late G_2 to after G_2 deformation.

The ore and alteration zones are dominantly, but not exclusively, spatially associated with the stratigraphically lower contact of a volcanic quartz ± feldspar porphyry (the Moose Lake porphyry). A "mafic fragmental" unit (altered felsic fragmental rock) and a barite horizon are spatially closely associated with the ore zones. The protolith of the ore is mainly the fragmental rock and the barite. The stratigraphically lower contact of the Moose Lake porphyry and the fragmental rock at the contact probably served as mechanical traps and the barite horizon as a chemical trap.

Introduction

THE HEMLO gold deposit contains more than 20 Moz of gold and is the site of three of the largest producing gold mines in Canada: the Williams mine, the Golden Giant mine, and the David Bell mine. After about 15 years of mining and many research efforts, several basic aspects of the deposit are still subject to debate, and little consensus on the genesis of the deposit has been reached.

Previous structural work has demonstrated that rocks in the Hemlo deposit area are affected by multiple generations of deformation (e.g., Patterson, 1983; Hugon, 1986; Kuhns et al., 1986, 1994; Muir and Elliott, 1987; Michibayashi, 1995; Muir, 1997). The deformation obscured critical primary geologic relationships and significantly modified the geometry of both the orebody and the host rocks. As a result, the stratigraphy and the nature of the protoliths of many of the lithologic units in the area are poorly understood. All these hamper the understanding of the processes responsible for the formation of the deposit.

To better understand the geologic processes that led to the genesis of the deposit, a major factor in developing an efficient exploration strategy for finding other Hemlo-type deposits, the Canadian Mining Industry Research Organization (CAMIRO) initiated a three year (1995–1997) multidisciplinary research project. The work reported here forms the geologic component of the project. During this work, the Hemlo area was mapped at a scale of 1:5,000 (map published at a scale of 1:10,000; Lin, 2001) and accessible crosscuts at all three mines were examined in detail. This work combines extensive surface mapping with detailed underground work, considers structures at scales ranging from microscopic to camp scales, integrates structural and stratigraphic studies, and considers the structures in three dimensions. The results have led to a better understanding of the stratigraphic and structural setting of the deposit and to better- constrained genetic models.

In this paper, the lithology and stratigraphy of the deposit area are first described, with emphasis on the stratigraphic setting of the deposit and the protoliths of the lithologic units that are closely associated with the ore. This material is followed by a detailed description of the structure of the area and a discussion of timing of alteration and mineralization with respect to magmatism, deformation, and metamorphism. The paper concludes with a discussion of the implications of the results of this study for the genesis of the deposit.

Geologic Setting

The Hemlo gold deposit is hosted in the Heron Bay-Hemlo greenstone belt of the Wawa subprovince of the Superior province, Ontario. The greenstone belt mainly consists of a sequence of Archean sedimentary and felsic, intermediate and mafic volcanic rocks ranging in age from ≥2720? Ma to ~2688 Ma (Corfu and Muir, 1989a; Davis, 1998; Jackson et al., 1998) (Fig. 1). Stratiform barite is documented at several localities 15 to 30 km west of the Hemlo deposit (Patterson, 1985), which is of special interest because barite is also present in the Hemlo deposit, spatially associated with the orebody.

All supracrustal rocks in the greenstone belt are metamorphosed. The metamorphic grades increase from upper

†E-mail: shoufa@uwaterloo.ca
*Present address: Department of Earth Sciences, University of Waterloo, Waterloo, ON N2L 3G1, Canada.

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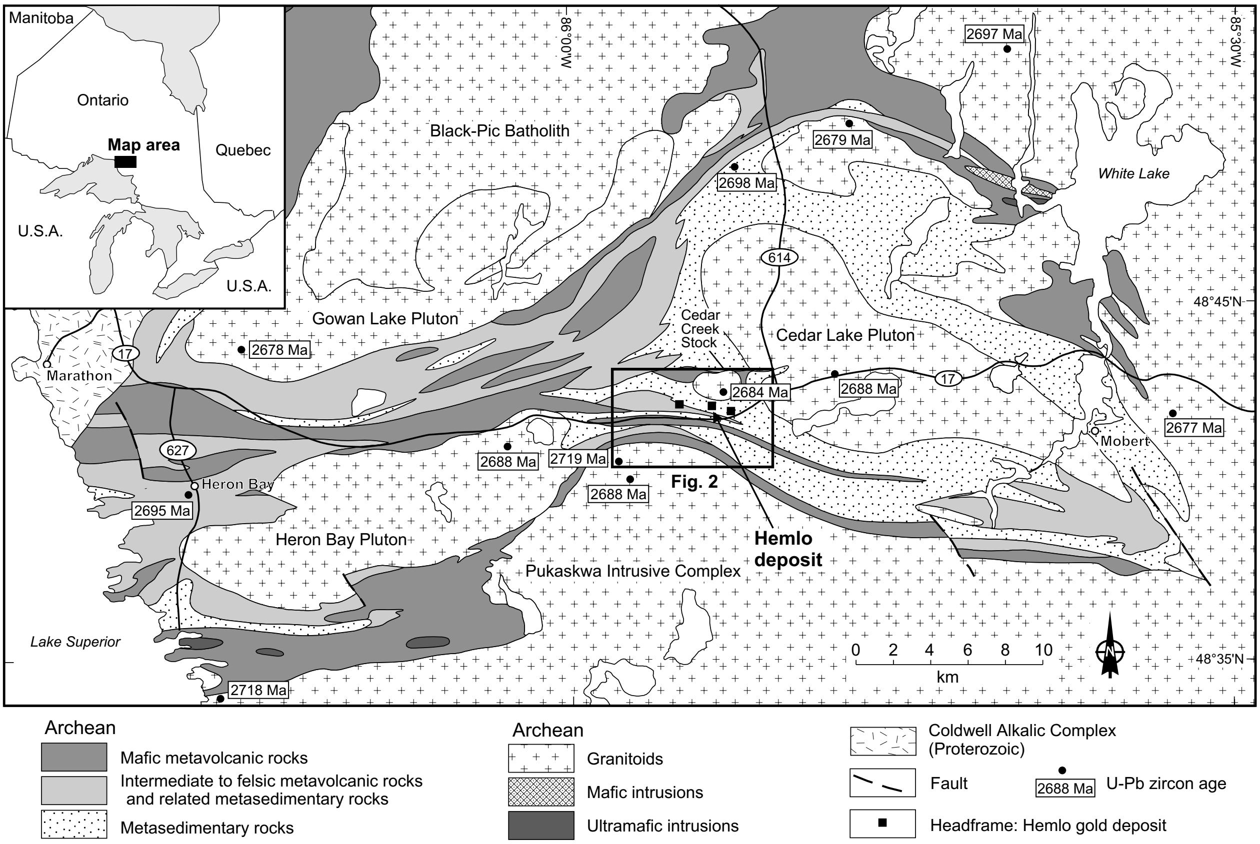

FIG. 1. Simplified geologic map of the Heron Bay-Hemlo greenstone belt, showing the regional geologic setting of the Hemlo gold deposit. The area mapped in detail during this study is indicated (area of Fig. 2). Modified from Muir (1997); U-Pb zircon ages from Corfu and Muir (1989a) and Jackson et al. (1998).

greenschist facies in the western part of the belt to middle amphibolite facies in the eastern part (including the Hemlo deposit area) (Muir, 1982a, b; Kuhns et al., 1994; Jackson et al., 1998; Powell et al., 1999). On the basis of titanite ages, Corfu and Muir (1989b) concluded that regional amphibolite-facies metamorphism occurred at ~2678 to 2676 Ma.

The greenstone belt is intruded by granodioritic-tonalitic plutons and related dikes (see Muir, 1997 and Jackson et al., 1998 for detailed description of the intrusive rocks). Major plutons include the Pukaskwa Intrusive Complex, the Heron Bay pluton, the Cedar Lake pluton, and the Gowan Lake pluton (Fig. 1). A marginal gneissic phase of the Pukaskwa complex yielded an U-Pb zircon age of ~2719 Ma, whereas an internal phase of the complex, the Heron Bay pluton and the Cedar Lake pluton, yielded U-Pb zircon ages of ~2688 Ma. The Cedar Creek stock has been dated at ~2684 Ma, and the Gowan Lake pluton and two other plutons at ~2679 to 2677 Ma (Fig. 1; ages from Corfu and Muir, 1989a; Jackson et al., 1998).

In the area around the Hemlo gold deposit (Figs. 2, 3), the supracrustal rocks include mafic and felsic volcanic rocks and sedimentary rocks (feldspathic wacke and conglomerate), most of which were deposited within a rather restricted time span of 2694 to 2688 Ma (U-Pb zircon ages; Davis, 1998). They are intruded by the Cedar Lake pluton, the Cedar Creek stock, feldspar porphyry dikes, and aplite dikes. The feldspar porphyry dikes are common in the area. The aplite dikes were observed only underground. Zircons from a feldspar porphyry dike and an aplite dike have yielded two essentially identical ages of 2677 ± 1.5 Ma (U-Pb zircon; Davis, 1998). The Archean rocks, as well as the structures and the ore zones described below, are cut by Paleoproterozoic diabase dikes (Fig. 3).

Rocks in the deposit area are strongly deformed. Deformation is most intense in the Hemlo (ductile) shear zone (Fig. 2). Located spatially in and near the southern edge of the shear zone is the Hemlo (brittle) fault (Fig. 3), which is probably a result of reactivation of the Hemlo shear zone.

The Hemlo gold deposit is located within the broad Hemlo shear zone (Figs. 2, 3). The vast majority of the ore occurs in two zones, referred to as the main and lower ore zones (Fig. 3). The main ore zone occurs at the contact between a quartz ± feldspar porphyry (the Moose Lake porphyry, unit AMLp) and a metasedimentary rock to the north (the hanging-wall sediments, part of unit Acw), and the lower ore zone occurs at or near the contact between the porphyry and a metasedimentary rock to the south (the footwall sediments, also part of unit Acw). Additional ore lenses occur in the Moose Lake porphyry and in the adjacent hanging-wall sediments. They include those at the "C" zone (pit) of the Williams mine, and the adjacent North zone (pit) and South zone in the Golden Sceptre property (Fig. 3). Significant alteration also occurs at

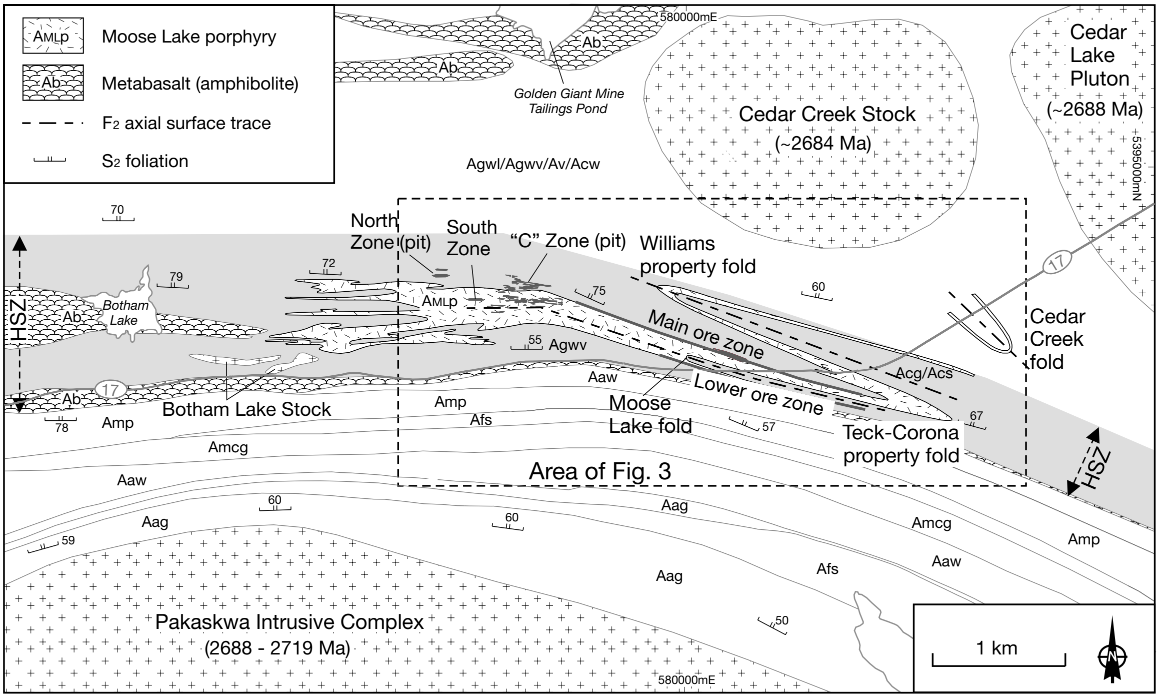

FIG. 2. Schematic diagram showing the structural outline of the Hemlo gold deposit area. Area of Fig. 3 is indicated. The U-Pb ages quoted are from Corfu and Muir (1989a). HSZ: Hemlo shear zone. See legend of Fig. 3 for additional explanation of abbreviations of unit names. Simplified from Lin (2001).

the barren sulfide zone that is located at the contact between a cummingtonite schist (unit Acs) and the Moose Lake porphyry (Fig. 3).

On the basis of a detailed study of alteration, mineralization, and geochemistry, Williams-Jones et al. (1998) conclude that mineralization at Hemlo includes one main event (Au-Mo-K event) followed by three remobilization events (Au-Sb-Si event, Au-Ca event and Au-As-Hg event, in chronologic order). During the main event, Au, S, Mo, Zn, As, Sb, Hg, Tl, and W were introduced and pervasive potassic alteration took place. The Au-Sb-Si event is characterized by precipitation of gold and stibnite in quartz veins, the Au-Ca event by calc-silicate alteration in which calc-silicate minerals (such as titanite, epidote, tremolite) occur as veins or replacement aggregates, and the relatively low temperature Au-As-Hg event by the precipitation of fine-grained realgar, cinnabar, and native arsenic. The main event is by far the most significant, as was recognized also by Kuhns et al. (1994). This paper is concerned with the main event unless otherwise indicated.

Supracrustal Rocks and Stratigraphy

The lithologic association south of the Hemlo shear zone is different from that within and north of the shear zone (Figs. 2, 3), and no correlation is attempted between the two areas. Major lithologic units south of the shear zone include an amphibolitic gneiss (unit Aag, mafic metavolcanic rocks), an amphibole-rich metawacke (unit Aaw), a felsic schist (unit Afs, feldspar-quartz schist), a metaconglomerate (unit Amcg), and a metapelite and metagraywacke (unit Amp). Because contacts between the units are mostly sheared or faulted and the rocks are mostly strongly deformed and metamorphosed, the stratigraphy cannot be confidently established. The reader is referred to Lin (2001) for a more detailed description of these units. Below we are concerned only with supracrustal rocks and stratigraphy within and north of the Hemlo shear zone (the immediate mine area).

The stratigraphy of the Hemlo deposit area was previously poorly understood. Guthrie (1984), Burk (1987), and Muir (1997) completed detailed lithologic mapping, but no interpretation of stratigraphy was presented. Kusins et al. (1991) divided rocks in the immediate mine area into the Rule Lake, Moose Lake, and Cedar Creek formations. However, these divisions were made before the recognition of the Moose Lake fold (this study) and need major revision. For example, their Cedar Creek formation contains stratigraphic correlatives of their Rule Lake formation, Moose Lake formation, and rocks that are not correlated with any of them. The difficulty in elucidation of stratigraphy is at least partly due to strong deformation and isoclinal folding, as well as to poor exposure.

Detailed mapping and structural analysis has led to a better understanding of the stratigraphic correlations in the immediate mine area. The proposed stratigraphic succession is shown in Fig. 4, and the units are described below in stratigraphic order. The younging direction of the sequence is based on (1) graded bedding in both the lower and upper graywacke (units Agwl and Agwu; see below) and (2) the observation and interpretation that the unit Acg conglomerate contains clasts from the Moose Lake porphyry (unit AMLp) and is unconformable on units AMLp and Agwu (see below).

Metabasalt (amphibolite, unit Ab)

Metabasalt (amphibolite) is exposed mainly in three areas: at the Golden Giant mine tailings pond, around Botham

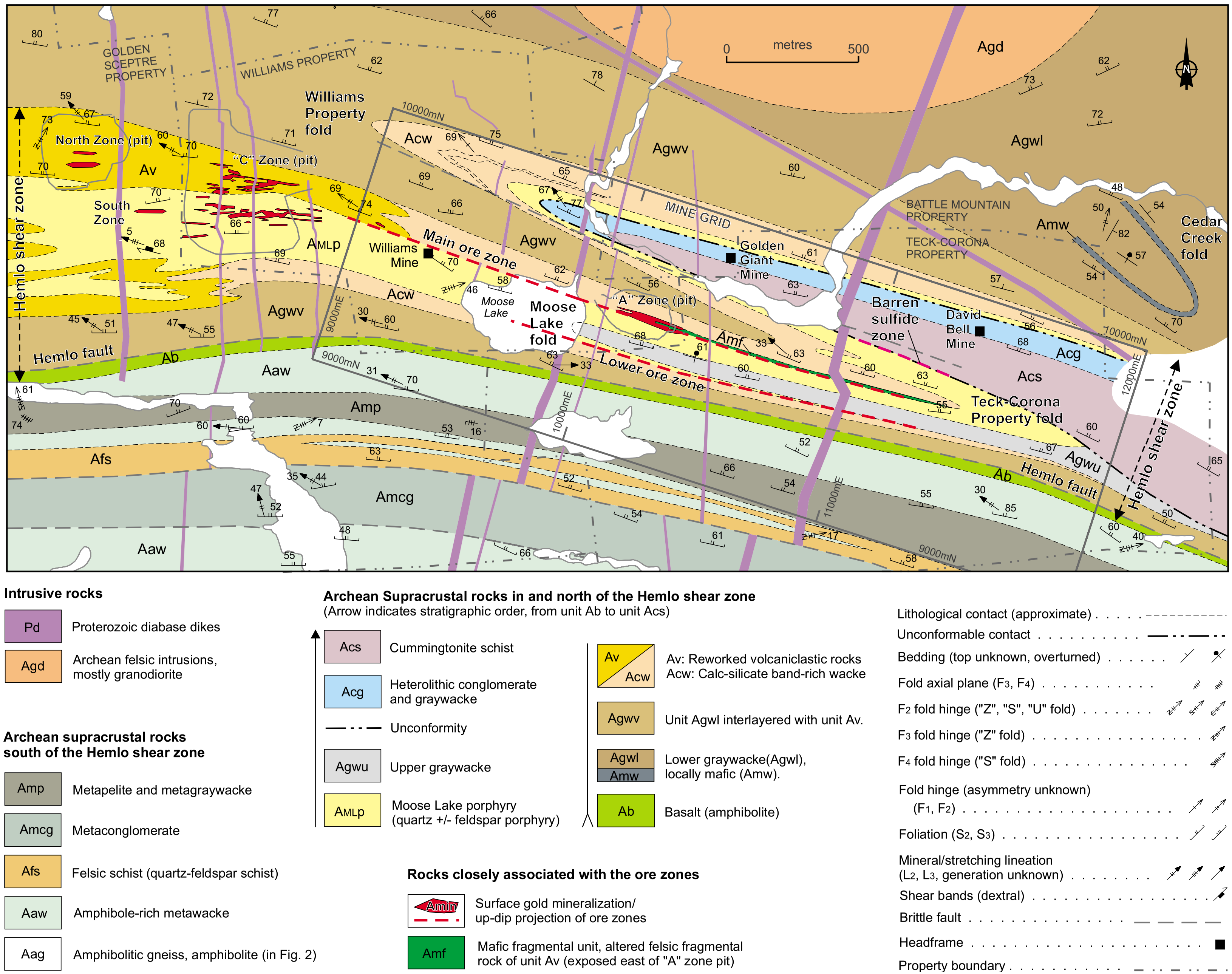

FIG. 3. Geologic map of the immediate Hemlo deposit area. Note that the main and lower ore zones coincide with the two limbs of the Moose Lake fold and occupy the same stratigraphic position (i.e., the folded contact between the Moose Lake porphyry [unit AMLp] and the calc-silicate-band–rich wacke [unit Acw]). The mine grid northings and eastings used by the three mines are shown. Simplified from part of a 1:10,000 scale geologic map (Lin, 2001).

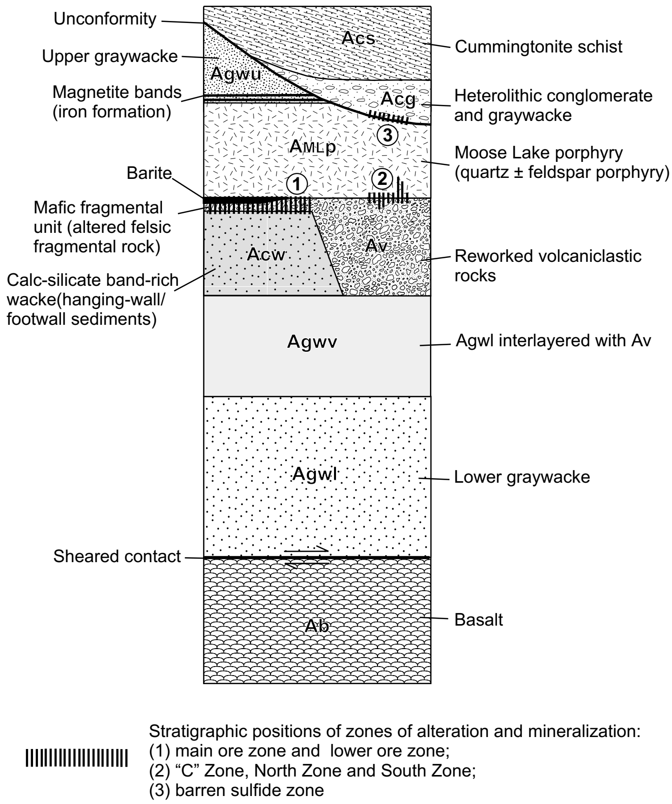

FIG. 4. Stratigraphy in the immediate Hemlo deposit area. The stratigraphic positions of zones of alteration and mineralization are indicated.

Lake, and along the southern edge of the Hemlo shear zone (Fig. 2). The last is mostly only a few tens of meters wide and can be traced across the map area for more than 8 km. Relict pillow structures are well preserved locally in all three areas (e.g., Fig. 5A).

The contacts between the metabasalt and other units are sheared where exposed. For example, at the Golden Giant mine tailings pond the unit is observed to be in shear zone contact with a feldspathic metawacke to the south (unit Agwl described below). Away from the contact, the metabasalt is weakly deformed and pillow structure is well preserved (Fig. 5A). Within ~20 m of the contact, the rocks are strongly sheared and a well-foliated and lineated mylonite is developed. Several feldspar porphyry dikes are intruded into the shear zone along the contact, parallel to the dominant foliation (Fig. 5B). The metabasalt along the southern edge of the Hemlo shear zone is also very strongly sheared, and its contact with other units on both sides is probably sheared. Therefore, the stratigraphic position of the metabasalt cannot be established. It is believed to be older than the units described below on the basis of regional considerations (e.g., by comparison with the Abitibi greenstone belt).

Lower graywacke (unit Agwl)

The lower graywacke is feldspathic. It is generally well bedded and contains well-developed graded bedding (Fig. 5C). Individual beds grade from wacke to siltstone or mudstone. They range from ~10 cm to tens of centimeters thick. A layer rich in biotite and hornblende (mafic wacke of Muir, 1997; unit Amw) is exposed in the eastern part of the map area.

Reworked volcaniclastic rocks (unit Av) and calc-silicate-band–rich wacke (unit Acw)

The reworked volcaniclastic rocks (unit Av) and calc-silicate-band–rich wacke (unit Acw) are lateral stratigraphic equivalents. The reworked volcaniclastic rocks (unit Av) occur in the west (Fig. 3). They are felsic to intermediate in composition and are commonly fragmental and heterolithic (Fig. 5D). These rocks are generally not well bedded and have a gradational relationship with the Moose Lake porphyry (unit AMLp) described below. In contrast to the porphyry, they contain few, if any, quartz "eyes" (Muir, 1997).

The reworked volcaniclastic rocks grade into banded wacke (unit Acw) in the east. The latter contains abundant calc-silicate bands (Fig. 5E). The former also contains some calc-silicate bands, especially near where the two grade into each other. The calc-silicate-band–rich wacke (unit Acw) forms the immediate structural hanging wall to the main ore zone and the immediate footwall to the lower ore zone (Fig. 3). In these two positions it is referred to as the hanging-wall and footwall sediments, respectively, by the mine geologists.

A vast majority of the calc-silicate bands are regular and concordant to bedding (Fig. 5E) and the calc-silicate-band–rich wacke can be traced from near the ore zones around fold closures into an area in the east where there is no evidence of extensive alteration related to mineralization (Fig. 3). These observations support the conclusion of Burk et al. (1986) that the calc-silicate bands are metamorphosed marly mudstone beds in a sedimentary protolith. The majority of the bands are thus unlikely to be a result of alteration as suggested by Pan and Fleet (1995) and Johnston (1996), although calc-silicate veins and pods that are discordant to bedding are locally present and may be a product of late-stage alteration.

Layers rich in aluminosilicate minerals (kyanite and/or sillimanite) are present in the calc-silicate-band–rich wacke (unit Acw). They are interpreted as metamorphosed aluminous sedimentary rocks (e.g., Burk et al., 1986). These layers have also been traced from near the ore zones around fold closures well to the east. Similar pelitic schists are also present to the south of the Hemlo shear zone, in unit Amp (metapelite and metagraywacke).

Near the ore zones, the hanging-wall and footwall sediments are muscovite-rich owing to sericitic alteration and subsequent metamorphism.

Moose Lake porphyry (unit AMLp)

The Moose Lake porphyry is felsic and consists of abundant quartz (± feldspar) phenocrysts in a fine-grained matrix (Fig. 6A). Muir (1982b, 1997), Burk et al. (1986) and Valliant and Bradbrook (1986) consider the unit as volcanic in origin. However, Johnston (1996) has suggested an intrusive origin. The following characteristics of this unit bear upon its interpreted origin.

1. The unit contains both massive and fragmental porphyry. Most clasts in the fragmental portion appear compositionally

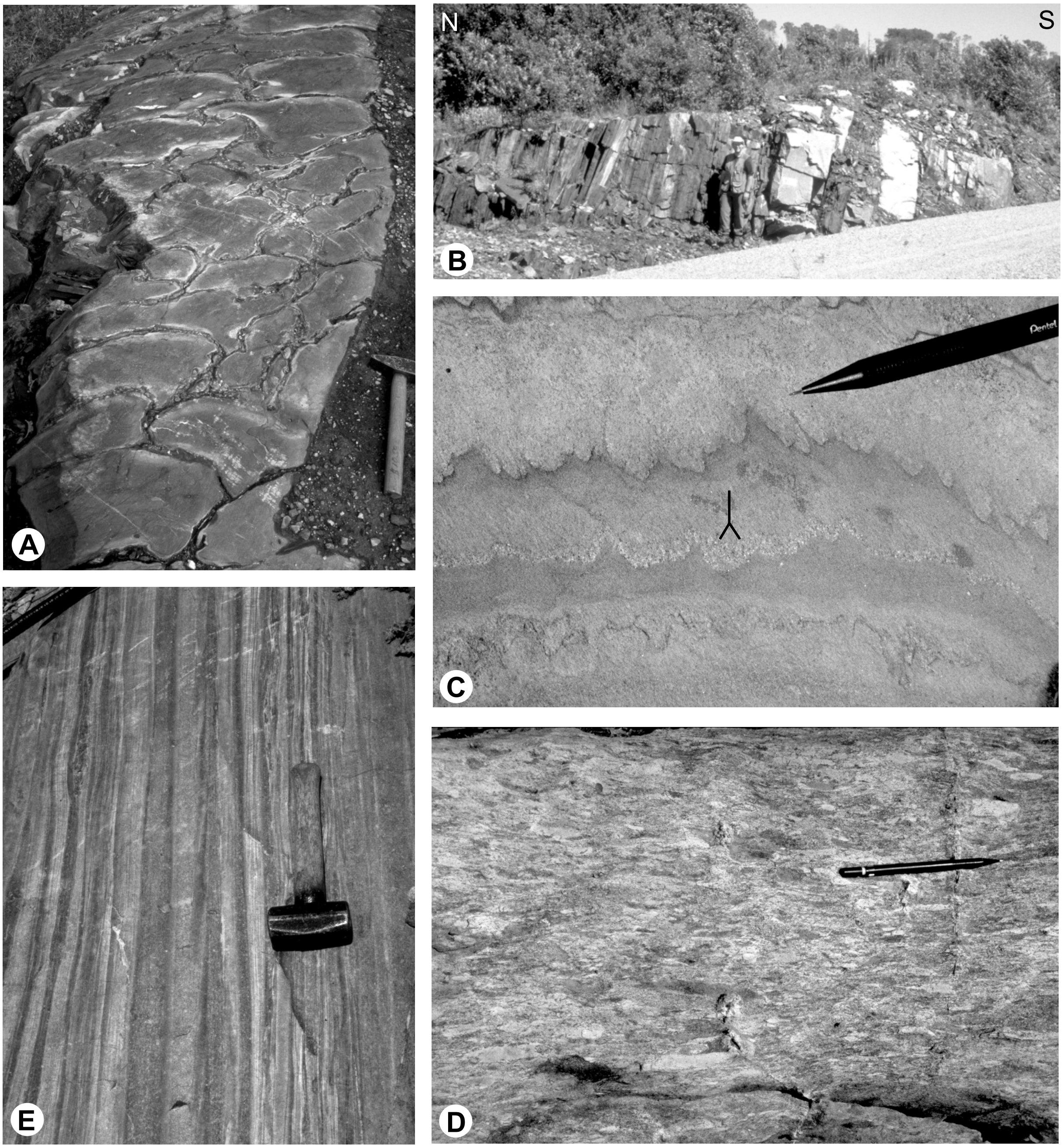

FIG. 5. A. Pillow structures in metabasalt (amphibolite, unit Ab), near the eastern shore of the Golden Giant mine tailings pond. B. Metabasalt (amphibolite, unit Ab) on the left in shear zone contact with lower graywacke (unit Agwl) on the right. Southern contact of the metabasalt at the Golden Giant mine tailings pond. Note feldspar porphyry dikes (white) in the (G_2) shear zone along the contact. In the Hemlo area, similar feldspar porphyry dikes dominantly occur in G_2 shear zones, suggesting that their intrusion was controlled by the shear zones. C. Graded bedding in lower graywacke (unit Agwl). Younging direction is indicated. Near western shore of the Golden Giant mine tailings pond. D. Reworked volcaniclastic rocks (unit Av) with polymictic fragmental texture. North zone pit. E. Calc-silicate-band–rich wacke (hanging-wall sediments, unit Acw). The darker bands are calc-silicate bands. At the entrance to the "A" zone pit. All photographed surfaces are subhorizontal except those in B.

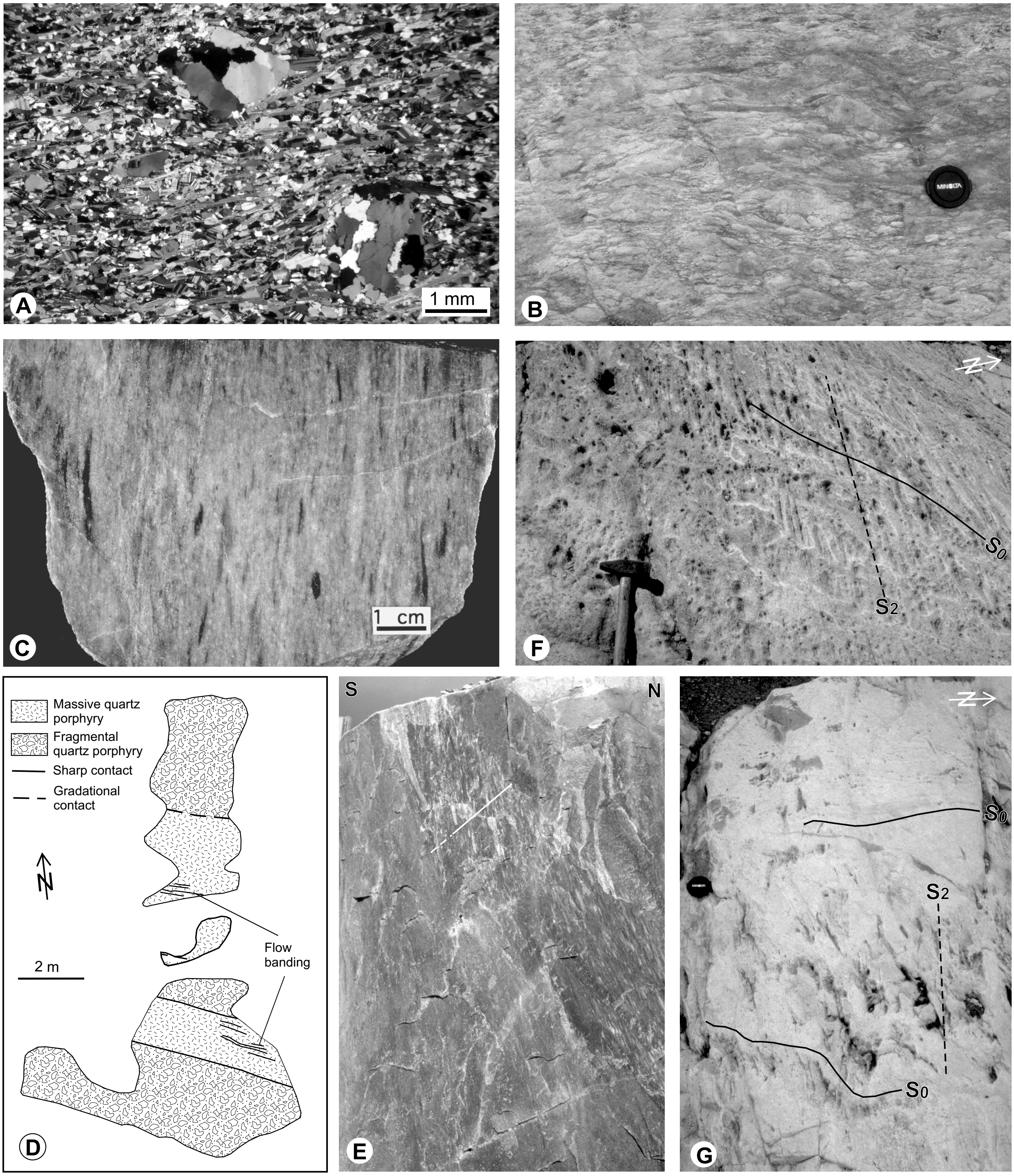

FIG. 6. A. Photomicrograph of the altered and metamorphosed Moose Lake porphyry (unit AMLp). The matrix is rich in microcline. Crossed nicols. B, C. Two examples of fragmental Moose Lake porphyry. Both are spatially closely associated with, and contain clasts identical to the massive Moose Lake porphyry. B is from the Golden Sceptre South zone and C is from the collection of the Williams mine. D. Sketch showing the field relationship between the fragmental and massive portions of the Moose Lake porphyry. Some contacts are gradational. Outcrop located in a north-trending trench near the southern edge of the North zone pit in the Golden Sceptre property. E. A layer of fragmental rock (indicated by the white line; about half a meter thick) in the massive Moose Lake porphyry. The lower contact of the fragmental layer is gradational. Near the office building of the Williams mine. F, G. Moose Lake porphyry with primary layering (S_0) folded by F_2 folds. The high-angle relationship between S_2 and S_0 is consistent with the interpretation that the outcrop is located close to the axial surface trace of a larger-scale F_2 fold (the Moose Lake fold). Both from the South zone of the Golden Sceptre property. The photographed surfaces in B, F, and G are subhorizontal.

and texturally identical to the massive portion (Fig. 6B, C). In the immediate mine area, both massive and fragmental rocks are present. They are spatially closely associated with each other and commonly have gradational contacts (Fig. 6D, E). Even in dominantly massive parts of the porphyry, layers of fragmental rocks are present (Fig. 6E). Laterally, the unit grades from massive and fragmental in the west to only fragmental in the east.

2. On weathered surfaces, the massive porphyry may appear compositionally and texturally heterogeneous and primary layering is locally clearly recognizable (Fig. 6F, G).

3. The unit does not cut across the stratigraphic units; it is bounded on one side by the calc-silicate-band–rich wacke (unit Acw) and on the other side by the upper graywacke (unit Agwu described below) (Fig. 3). Units Acw and Agwu are distinct lithologically (this study) and geochemically (Williams-Jones et al., 1998) and contain different detrital zircon populations (Davis, 1998). The latter indicates different sedimentary sources.

These observations are most consistent with a volcanic origin for the porphyry.

In the immediate mine area, the porphyry is separated from the hanging-wall sediments by a mafic fragmental unit (unit Amf below) and/or the ore, and strong deformation and alteration make it difficult to directly determine the nature of the contact between porphyry and sediment. However, the two units must have been conformable because both units have gradational contacts with the reworked volcaniclastic rocks (unit Av) that are the stratigraphic correlative of the hanging-wall and footwall sediments.

Near its contact with the ore, the porphyry is sericitized and metamorphosed to form a muscovite schist with relict quartz phenocrysts, termed the quartz-eye sericite schist by the mine geologists.

Upper graywacke (unit Agwu)

The upper graywacke occurs between the two limbs of the folded Moose Lake porphyry to the east of Moose Lake (Fig. 3). It is feldspathic and moderately to well bedded. It consists mainly of feldspar + biotite ± garnet ± quartz. Well-preserved bedding with local grading (Fig. 7A) indicates that the rock is sedimentary in origin (see also Guthrie, 1984; Muir, 1997). On fresh surfaces (underground and on drill core), the unit appears dark colored and partly massive (Fig. 7B, the lowest core), charactereistics that may have led to the suggestion that it is a metadiorite (Johnston, 1996).

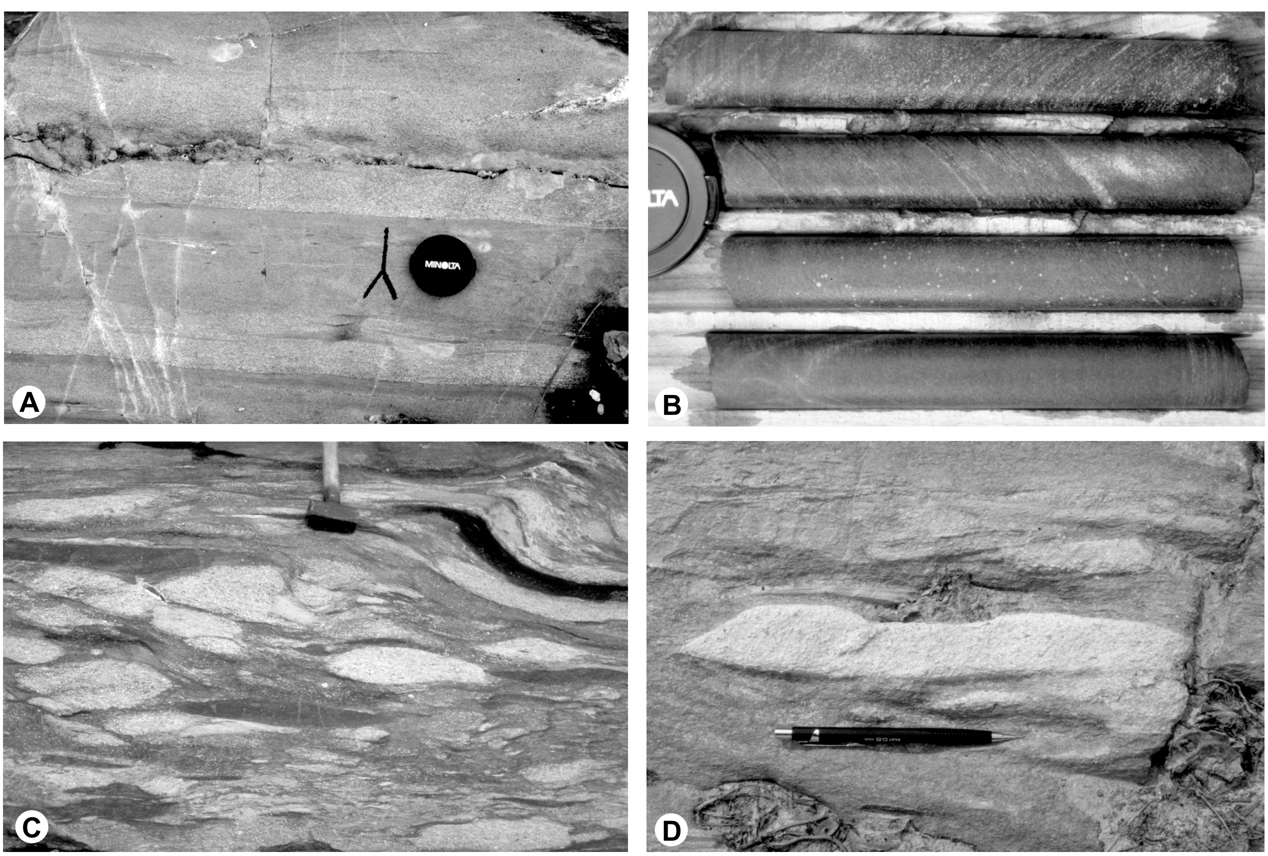

FIG. 7. A. The upper graywacke (unit Agwu) with graded bedding. Younging direction is indicated. North side of Highway 17 near turnoff to the "A" zone pit. B. Representative drill cores of the upper graywacke. The upper two contain magnetite-calc-silicate bands. The third contains garnet porphyroblasts (light-colored specks) and the fourth appears massive. C. Heterolithic conglomerate (unit Acg). North side of Highway 17, behind the headframe of the David Bell mine. D. Heterolithic conglomerate (unit Acg) with a clast of quartz porphyry. North shore of Polishing Pond on the Williams property. The photographed surfaces in A, C, and D are subhorizontal.

The unit typically contains magnetite. At the stratigraphic base of the unit, near its contact with the underlying Moose Lake porphyry, it contains abundant magnetite bands (Fig. 7B, the upper two cores) and local oxide-facies iron formation.

Heterolithic conglomerate and graywacke (unit Acg)

The unit consists of conglomerate interlayered with feldspathic graywacke. The conglomerate consists of pebble- to boulder- (mostly cobble-) sized clasts in a graywacke matrix (Fig. 7C). It is matrix supported to clast supported. The clasts are mainly intermediate to felsic in composition (mainly feldspar porphyry). Some mafic schist clasts are also present.

At an outcrop within the Williams property (north shore of Polishing Pond), clasts of quartz porphyry are found in the conglomerate (Fig. 7D). At the outcrop, the conglomerate is separated from the Moose Lake porphyry by a pelitic schist ~3 m wide. The quartz porphyry clasts appear identical to, and are interpreted to have been derived from, the Moose Lake porphyry. This interpretation is supported by the fact that the conglomerate and graywacke unit contains detrital zircons of ~2800 Ma that otherwise occur only in the Moose Lake porphyry (as inheritance; Davis, 1998). These observations and interpretation, as well as the map distribution of the unit and the associated cummingtonite schist (unit Acs) described below, indicate that these two units are probably unconformable on the Moose Lake porphyry (AMLp) and upper graywacke (Agwu) (Fig. 3).

Cummingtonite schist (unit Acs)

Overlying the heterolithic conglomerate is a cummingtonite schist. It consists of cummingtonite, plagioclase, biotite, and quartz and contains thin layers consisting of hornblende, cummingtonite, quartz, and plagioclase. The Fe- and Mg-rich cummingtonite schist has been interpreted as a metamorphosed Fe-Mg-carbonate unit rich in clastic impurities (Burk et al., 1986).

Lithologies Closely Associated with the Ore and Alteration Zones

Detailed description of mineralization and alteration is beyond the scope of this study. For the convenience of later discussion, lithologies closely associated with the ore and alteration zones are summarized below, with emphases on the distribution of alteration zones and the nature of a mafic fragmental unit and the protolith of the ore.

Ore lithology (unit Amin)

Both the main and lower ore zones at Hemlo consist of feldspathic ore, sericitic ore, and several minor types of ore. The ore is variably enriched in Mo (molybdenite), Au (native gold), As (realgar), Hg (cinnabar), Sb (stibnite and native antimony), Ba (barite and barium-rich microcline), V (green vanadium-rich mica), Tl, Zn, and W (Harris, 1989; Powell and Pattison, 1997; Williams-Jones et al., 1998). Gold is disseminated in the ore.

The feldspathic ore is a massive to banded to fragmental rock that consists of microcline (40–55%, locally up to 90%), quartz (10–40%), muscovite, green (vanadium-rich) mica, and minor biotite (Kuhns, 1986). It normally contains 3 percent to 35 percent pyrite and molybdenite. The latter gives the rock a bluish color and is a good indicator of gold. The feldspathic ore is typically high grade.

The sericitic ore is strongly foliated. It is composed of quartz (40–60%), muscovite (15–30%, locally up to 60%), feldspar, biotite, and green mica (Kuhns, 1986). It contains up to 15 percent pyrite and traces of molybdenite. Typically, the sericitic ore is not as high grade as the feldspathic ore, which it tends to envelope.

Au-bearing quartz veins at Hemlo formed during the Au-Sb-Si remobilization event mentioned above. They have a widespread distribution but are volumetrically minor. Carbonate veins are absent.

Alteration

Alteration at both the main and lower ore zones consists of an inner K feldspathic zone grading outward into sericitic zones (Fig. 8; Kuhns, 1986). The feldspathic ore is associated with the feldspathic zone and the sericitic ore with the sericitic zone. Alteration zones are spatially much more extensive than the ore zones themselves, especially the sericitic alteration zone that extends into the Moose Lake porphyry on

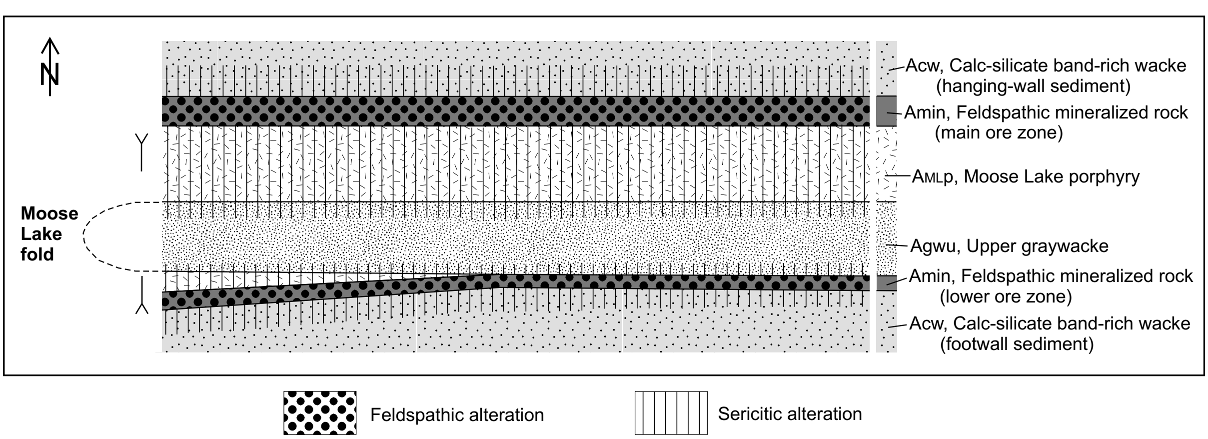

FIG. 8. Schematic diagram showing the distribution of alteration zones vs. the distribution of major lithologic units at Hemlo. The alteration zones are centered along the northern and southern contacts (folded equivalents) of the Moose Lake porphyry (AMLp) with the hanging-wall and footwall sediments (Acw), or the stratigraphically lower contact of the porphyry, and they are not symmetric about the Moose Lake porphyry itself.

one side and into the hanging-wall and footwall sediments on the other side of the ore zones. Near the west end of both the main and lower ore zones, zones of feldspathic alteration are of only subore grade. The alteration zones are centered along the northern and southern contacts (folded equivalents) of the Moose Lake porphyry with the hanging-wall and footwall sediments, or the stratigraphically lower contact of the porphyry (Fig. 8). They are not centerd along the stratigraphically upper contact of the porphyry (the contact between the porphyry and the upper graywacke, unit Agwu). The alteration zones are therefore not symmetric about the Moose Lake porphyry itself.

Barite

Barite is spatially associated with both the main and lower ore zones and forms part of the baritic ore. It is banded and has isotopic signatures similar to sedimentary barite exposed west of Hemlo and is thus interpreted to be sedimentary in origin (Cameron and Hattori, 1985; Thode et al., 1991).

Mafic fragmental unit (unit Amf)

A rock unit referred to by mine geologists as the mafic fragmental is spatially associated with the ore. It occurs at the contact between the Moose Lake porphyry and hanging-wall sediments, and consists of felsic fragments in a biotite-rich matrix (Fig. 9A).

The mafic fragmental unit has been variously interpreted as a metaconglomerate (Burk et al., 1986), a mafic volcaniclastic rock (Valliant and Bradbrook, 1986) and as a hydrothermal breccia (Johnston, 1996). The felsic composition of the fragments makes it unlikely to be a mafic volcaniclastic rock and the concordant nature of the unit does not support a hydrothermal breccia. The unit is also unlikely to be a fault breccia because the clasts are different from the enclosing units (the hanging-wall sediments and the Moose Lake porphyry). It is most likely an altered felsic fragmental rock correlative with those in the reworked volcaniclastic rocks (unit Av). Patches of biotite alteration are present in the latter rocks in the North zone area. At level 5 of the David Bell mine, a felsic fragmental rock similar to that at the North zone occupies a position identical to that of, and can be traced into, the mafic fragmental unit. In the transition zone, the felsic fragmental rock is partly altered and contains discrete zones rich in biotite (Fig. 10A). Like the mafic fragmental unit, it has a gradational contact with the ore that has relict fragmental features (Fig. 10B; see discussion below). In a newly dug trench in the Teck-Corona property, the mafic fragmental unit is observed to grade into a felsic fragmental rock with the latter containing patches of biotite alteration.

At one outcrop along Highway 17, along strike of the mafic fragmental unit at the "A" zone pit of the Williams mine and immediately north of the Moose Lake porphyry, a fragmental rock with quartz phenocrysts, probably part of the fragmental Moose Lake porphyry, has a biotitic matrix. This indicates that part of the mafic fragmental unit could be altered fragmental Moose Lake porphyry. However, this is not generally true, because clasts with quartz phenocrysts are rare in most of the mafic fragmental unit.

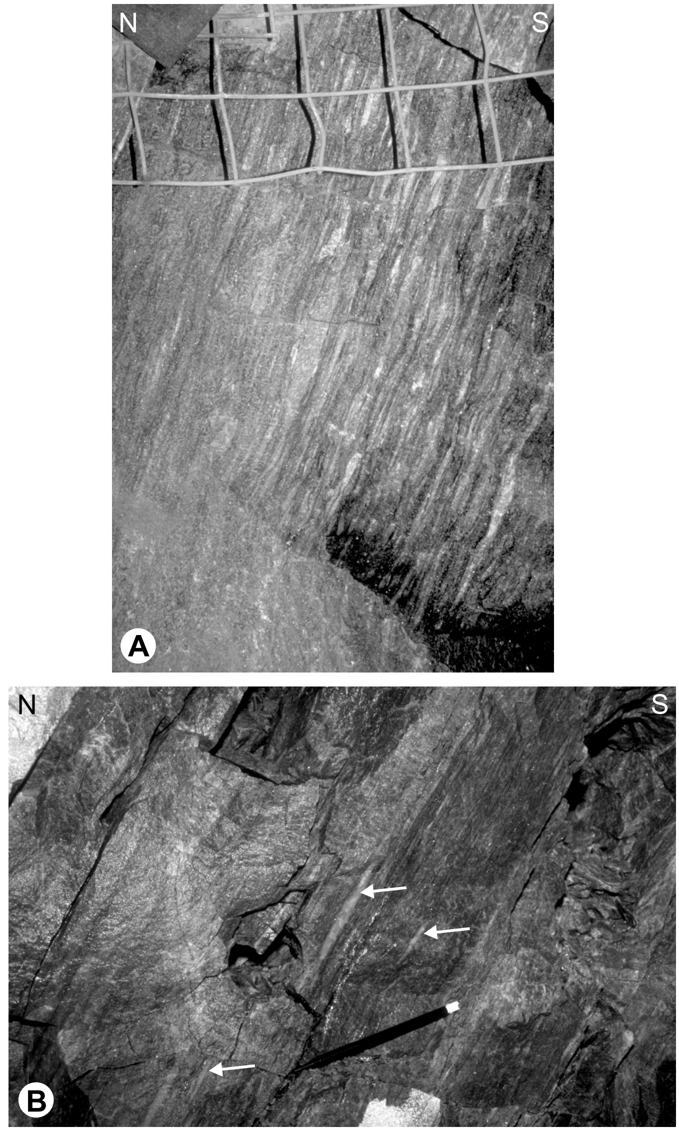

FIG. 9. A. A mafic fragmental rock (unit Amf) consisting of felsic fragments in a biotite-rich matrix, interpreted to be an altered felsic fragmental rock. B. Feldspathic ore with relict fragmental texture, interpreted as a mineralized fragmental rock. Some of the relict fragments are indicated by white arrows. Both from underground at the Golden Giant mine.

Protolith of the ore

The following observations and discussion are concerned with the nature of the protolith of the ore:

1. The contact between the ore and the (sericitized) massive Moose Lake porphyry is extremely sharp (Fig. 10C) and can generally be confidently determined without gold assay. The ore rarely contains quartz phenocrysts. These observations indicate that the protolith of the majority of the ore is not the quartz porphyry, a conclusion supported by geochemical data (Williams-Jones et al., 1998). Locally, where fragmental portions of the porphyry are in contact with the ore, it is mineralized, occasionally to ore grade (e.g., the ore exposure at Highway 17, field trip stop 20A of Muir et al., 1991).

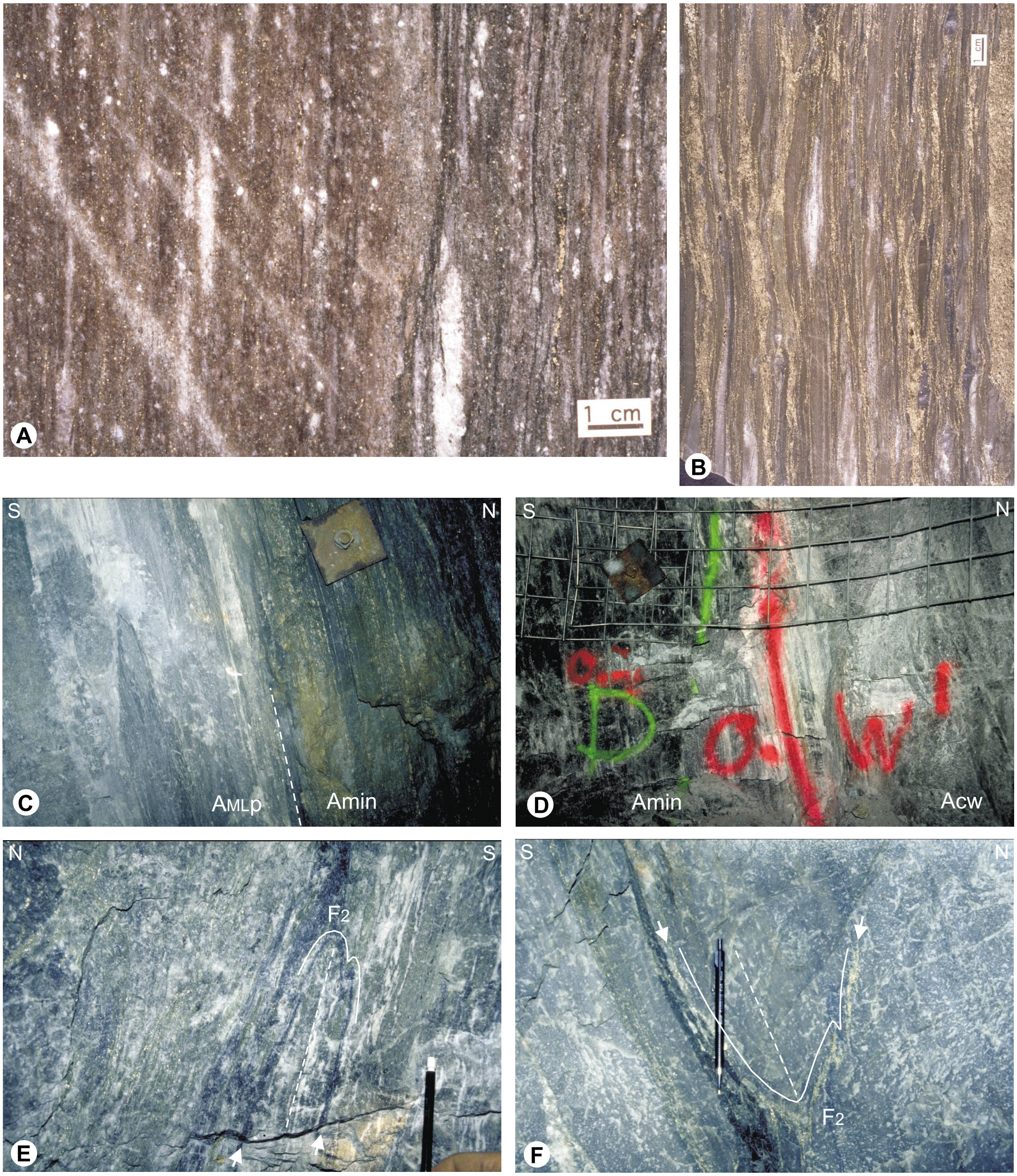

FIG. 10. A. A polished slab of a felsic fragmental rock that is partly altered on the right to become a biotite-rich mafic fragmental rock. Biotite alteration is concentrated in narrow foliation-parallel bands (dark colored). These observations support the interpretation that the mafic fragmental unit is an altered felsic fragmental rock. B. A polished slab of ore with relict fragmental texture. Samples A and B are from level 5 of the David Bell mine where the felsic fragmental rock grades into the mafic fragmental unit, which in turn grades into the fragmental ore, indicating that the fragmental rock is the protolith of the ore. C. Contact between the sericitized Moose Lake porphyry (AMLp) on the left and the main ore zone (Amin) on the right. The contact is generally very sharp. Note the S_2 foliation defined by pyrite bands in the ore. Underground at the Golden Giant mine. D. Contact between the main ore zone (Amin) on the left and the hanging-wall sediments (Acw) on the right. It is gradational and assays are needed to determine the ore-waste contact. Underground at the Williams mine. E, F. Examples of ore with F_2 folds. The fold in E is shown by a deformed molybdenite seam in a feldspathic ore; that in F, by a deformed pyrite vein in a feldspathic ore. In each case, the two limbs of the fold are indicated by white arrows. Note that both folds have well-developed axial planar foliation (S_2), and the pyrite vein in F is partly transposed into the S_2 foliation. Underground at the Golden Giant mine.

2. The mafic fragmental unit is spatially closely associated with the ore, is generally mineralized to subore grade (1–2 g/t Au), and in many places has gradational contact with the ore (e.g., Fig. 10A, B). Relict fragmental features are common in the ore (Figs. 9B, 10B). It is therefore likely that the mafic fragmental unit (or more precisely its protolith) is the main protolith of the ore (compare Fig. 9A with 9B, and 10A with 10B; see also Burk, 1987). This interpretation is strongly supported by the observation at the David Bell mine, where the mafic fragmental unit is best preserved, that the main ore zone cuts across the fragmental unit and that the thickness of the main ore zone is antithetic to the thickness of the mafic fragmental unit (Fig. 11; see also fig. 7 of Burk et al., 1986). Such an antithetic relationship is expected assuming that the fragmental unit had a more or less constant thickness before mineralization and was partly mineralized. Exceptions to this generalization may occur because the thickness of the fragmental unit before mineralization may not be constant and the fragmental rock is not the only protolith of the ore.

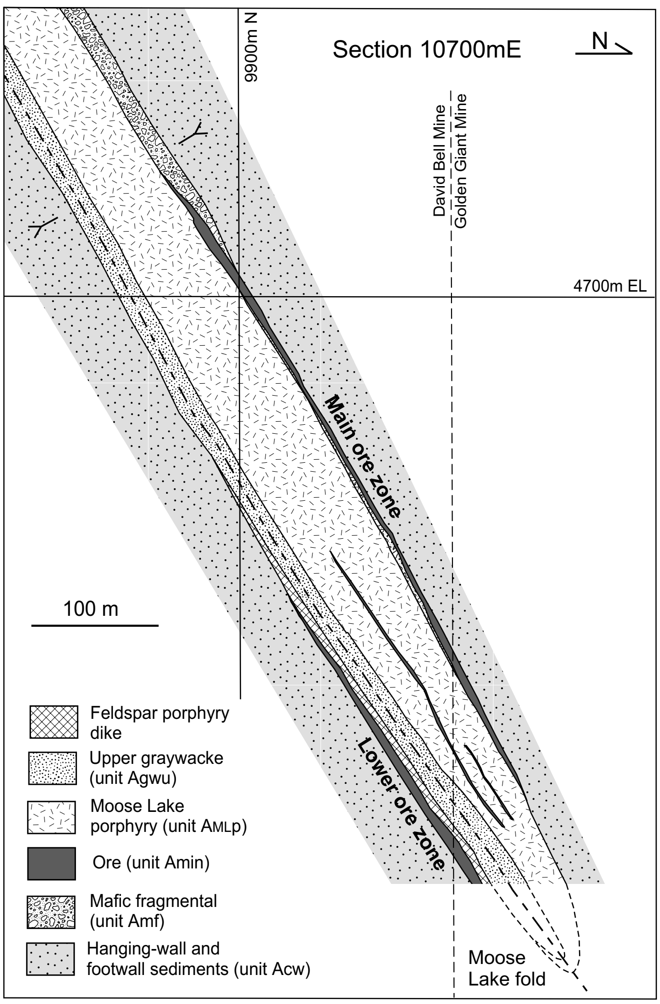

FIG. 11. Section 10700mE (looking west) of the David Bell/Golden Giant mine showing the close spatial relationship between the main ore zone and the mafic fragmental unit, and the antithetic relationship between the thicknesses of the two units. Note that the main ore zone cuts across the fragmental rock. The latter occurs on the footwall side of the ore zone below the 4700 m level and on the hanging-wall side above the 4700 m level. The spatial relationship strongly supports that the fragmental rock is the main protolith of the ore. Redrawn with minor modification after a diagram from the David Bell mine. Note that the mine grid northings and eastings in this figure, as well as in Figures 19 and 23, are shown in Figure 3. The grid elevation used here is based on that of the Golden Giant and David Bell mines, and it is defined as height above sea level plus 5,000 m. In this grid, the surface of Moose Lake in the center of Figure 3 has an elevation of 5,313 m.)

3. As described above, sedimentary barite is closely associated with the ore zones. It is clearly the protolith of the baritic ore.

4. The contacts between the ore and the hanging-wall and footwall sediments are generally gradational (Fig. 10D), and assays are generally needed to determine the ore-waste contact. It is likely that part of the ore is mineralized hanging-wall and footwall sediments.

Structural Geology

On the basis of overprinting relationships and fold styles, four generations of ductile shearing and folding as well as brittle faulting are recognized in the Hemlo area. They are broadly consistent with those described in Muir and Elliott (1987), although those authors are mostly concerned with mesoscopic structures. The four generations of ductile structures are here termed G_1 to G_4, and the associated folds, foliation, and lineation, where present, are termed F_1 to F_4, S_1 to S_4, and L_1 to L_4, respectively.

The connotation "G" is used here, instead of "D," because the four *generations* of structures (G) do not necessarily correspond to four discrete *episodes* of deformation (D). Structures are grouped into generations on the basis of overprinting relationships and styles, and more than one generation of structures may develop in a single episode of progressive deformation (see Mawer and Williams, 1991, and references therein).

First-generation (G_1) structures

Evidence for G_1 deformation is scarce. Its presence is indicated by a locally preserved foliation (S_1) and folds (F_1) that are overprinted by the main regional foliation (S_2) and associated folds (F_2). For example:

1. At an outcrop in the calc-silicate-band–rich wacke (unit Acw) in the Williams property (the "back 40's outcrop"), a doubly plunging fold (F_1), possibly a sheath fold, is overprinted by F_2 folds (Fig. 12A). At an outcrop in the mafic metavolcanics, F_1 folds are overprinted by both F_2 and F_{3a} folds (Fig. 12B).

2. At an outcrop in the northern margin of the Pukaskwa Intrusive Complex, a foliation (S_1) is folded by F_2 (Fig. 12C).

G_1 structures are spatially closely associated with, and have a style very similar to that of, G_2 structures. No macroscopic G_1 structures have been recognized. It is likely that both G_1 and G_2 structures are related to a single progressive deformation event (episode). This interpretation means that G_1 and G_2 structures cannot really be separated in time terms, and G_1 structures at one outcrop do not have to be older than G_2 structures at another outcrop.

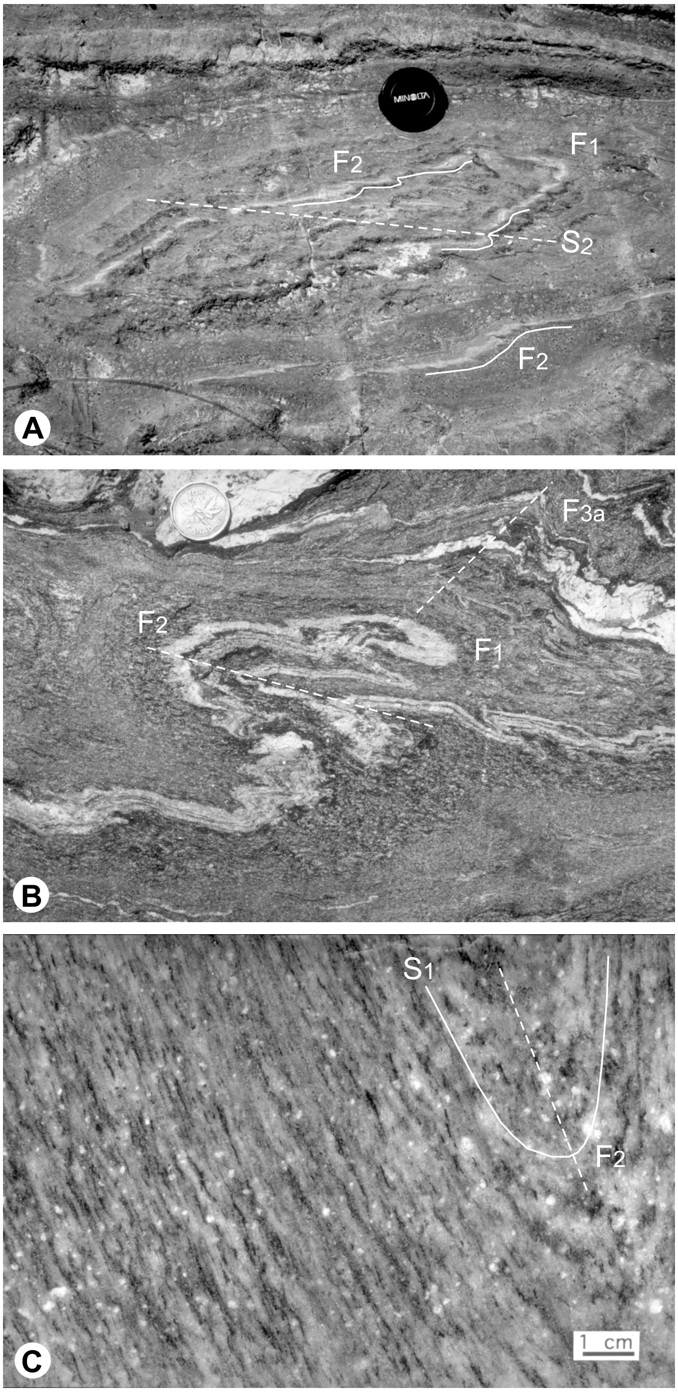

FIG. 12. A. A doubly plunging F_1 fold (sheath fold?) overprinted by F_2 folds. The F_2 folds have "S" asymmetry. Subhorizontal surface. Back 40's outcrop, Williams property. B. Overprinting relationship among F_1, F_2, and F_{3a} folds in an amphibolite. Subhorizontal surface. South of the Hemlo shear zone. C. A sample from within the northern margin of the Pukaskwa Intrusive Complex, showing an S_1 foliation folded by an F_2 fold. The F_2 fold has a clear axial-planar cleavage.

Second-generation (G_2) mesoscopic (outcrop-scale) structures

During G_2 deformation, the rocks were strongly deformed, and folds (F_2), a foliation (S_2) and a lineation (L_2) were developed throughout the map area. G_2 structures are the dominant features in most outcrops.

The S_2 foliation is defined by a preferred orientation of mafic minerals (biotite and hornblende) and clasts in conglomerate and volcaniclastic rocks, and by compositional layering with layers rich in biotite and/or hornblende alternating with those rich in feldspar ± quartz. S_2 foliation dips steeply (mostly 60°–75°) to the north or north-northeast. To the south of the Hemlo shear zone, it strikes east-northeasterly in the west and gradually curves to east-southeast in the east, following the trend of the northern margin of the Pukaskwa Intrusive Complex (Fig. 2). In the Hemlo shear zone (Fig. 2), the foliation strikes easterly at and to the west of the "C" zone pit and turns to an east-southeast direction to the east of the pit (Figs. 2, 13).

The L_2 lineation, developed on the S_2 foliation, is defined by a preferred orientation of biotite and/or hornblende in the foliation, by elongate clasts in conglomerate and volcaniclastic rocks (Fig. 14A, B), and by elongate varioles(?) in mafic volcanic rocks (Fig. 14C). To the west of the "C" zone pit, the lineation is well developed. It pitches steeply west on the S_2 foliation or plunges moderately to steeply to the northwest (Fig. 13A). To the east of the pit, the lineation is not as well developed. Where it is observed, it plunges moderately to steeply to the west to northwest (Fig. 13B).

F_2 folds are generally tight to isoclinal, and have well-developed axial planar foliation (S_2). The F_2 fold hinges are rarely exposed. Where observed, they are mostly subparallel to the L_2 lineation. F_2 hinges highly oblique to the lineation are also present, indicating that the F_2 folds are noncylindrical. Where the fold asymmetry can be determined, most F_2 folds have "S" asymmetry looking down plunge (e.g., Fig. 12A). At one outcrop, "Z"- and "S"-shaped F_2 folds appear together, having the geometry of a sheath fold (Fig. 15C).

Macroscopic (camp-scale) F_2 folds

The map pattern of the Hemlo camp is dominated by macroscopic F_2 folds (Figs. 2, 3). Four such folds are present in the immediate mine area: the Cedar Creek fold, the Williams property fold, the Teck-Corona property fold and the Moose Lake fold (Figs. 2, 3). The Cedar Creek fold occurs in the lower graywacke (unit Agwl). The other three folds affect the same horizon: the Moose Lake porphyry (unit AMLp) and units stratigraphically above and below it. All four folds have a very similar style and scale. They are tight to isoclinal with a well-developed axial planar foliation (S_2). The latter three folds have "S" asymmetry on the camp scale (Fig. 2).

Cedar Creek fold: The Cedar Creek fold occurs in the eastern part of the map area (Fig. 3) and has been mapped by previous workers (Kuhns et al., 1994; Muir, 1997). The presence of the fold is clearly indicated by the following observations at an extensive outcrop at Highway 17 near Cedar Creek (Fig. 16): (1) the repetition of a mafic layer (unit Amw) ~20 m thick, interpreted by Muir (1997) as a mafic wacke, (2) reversal of younging direction, (3) systematic variation of F_2 fold symmetry from "S" to "M" to "Z," and (4) reversal of the

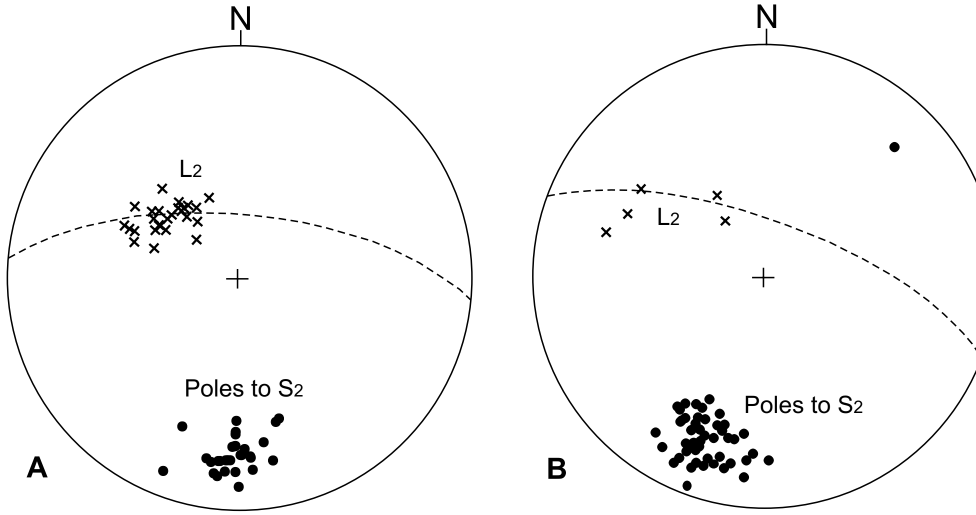

FIG. 13. Equal-area lower-hemisphere projection of poles to S_2 foliation and L_2 lineation in the Hemlo shear zone. A. Data from the area west of the "C" zone pit. Structural trend in the area is east-west. B. Data from the area east of the "C" zone pit, or the area of the two ore zones. Structural trend in the area is east-southeast.

relationship between bedding (S_0) and foliation (S_2). In the hinge area, the F_2 folds have "M" symmetry and the S_2 foliation is at high angle to the bedding. The axial plane of the fold strikes southeasterly and the hinge plunges northeasterly. The latter is based on direct observation of mesoscopic parasitic F_2 fold hinges and interpretation of S_2/S_0 data (Fig. 16).

Williams property fold: The Williams property fold is well defined and has been shown on most previous maps (e.g., Guthrie, 1984; Kuhns, 1988; Muir, 1997). The closure of the fold occurs in the northeastern part of the Williams property (Fig. 3). Marker units that can be traced around the fold closure include the calc-silicate-band–rich wacke (unit Acw), the

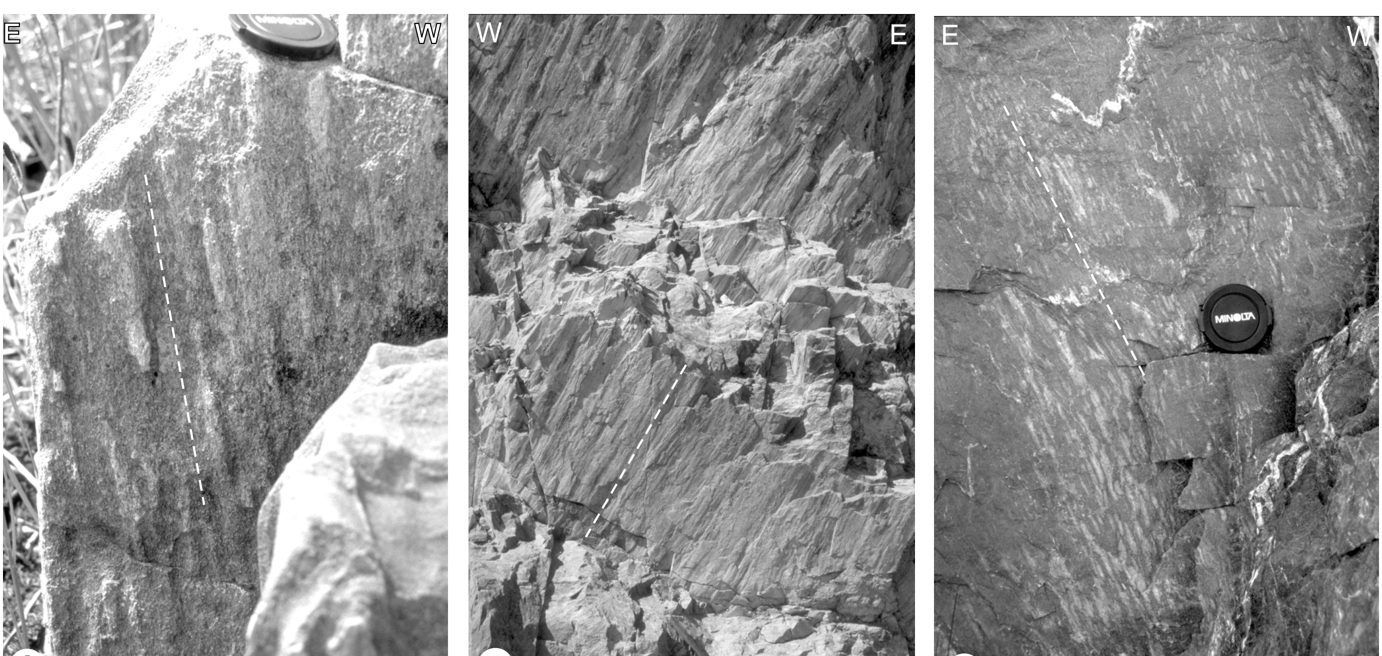

FIG. 14. A. L_2 lineation defined by elongate clasts in a conglomerate. Note that the clasts are strongly elongated parallel to the lineation but are only weakly elongated on the surface perpendicular to the lineation (the upper surface). The strain ellipsoid is thus prolate or close to cigar shaped. South shore of Botham Lake. B. L_2 lineation parallel to the long dimension of elongated clasts in fragmental rocks. Hammer near the lower edge for scale. North side of Highway 17, west of Williams mine. C. L_2 lineation defined by elongate varioles(?) in mafic volcanic rocks. South side of Highway 17 near turnoff to the radio tower (or to the Hemlo station).

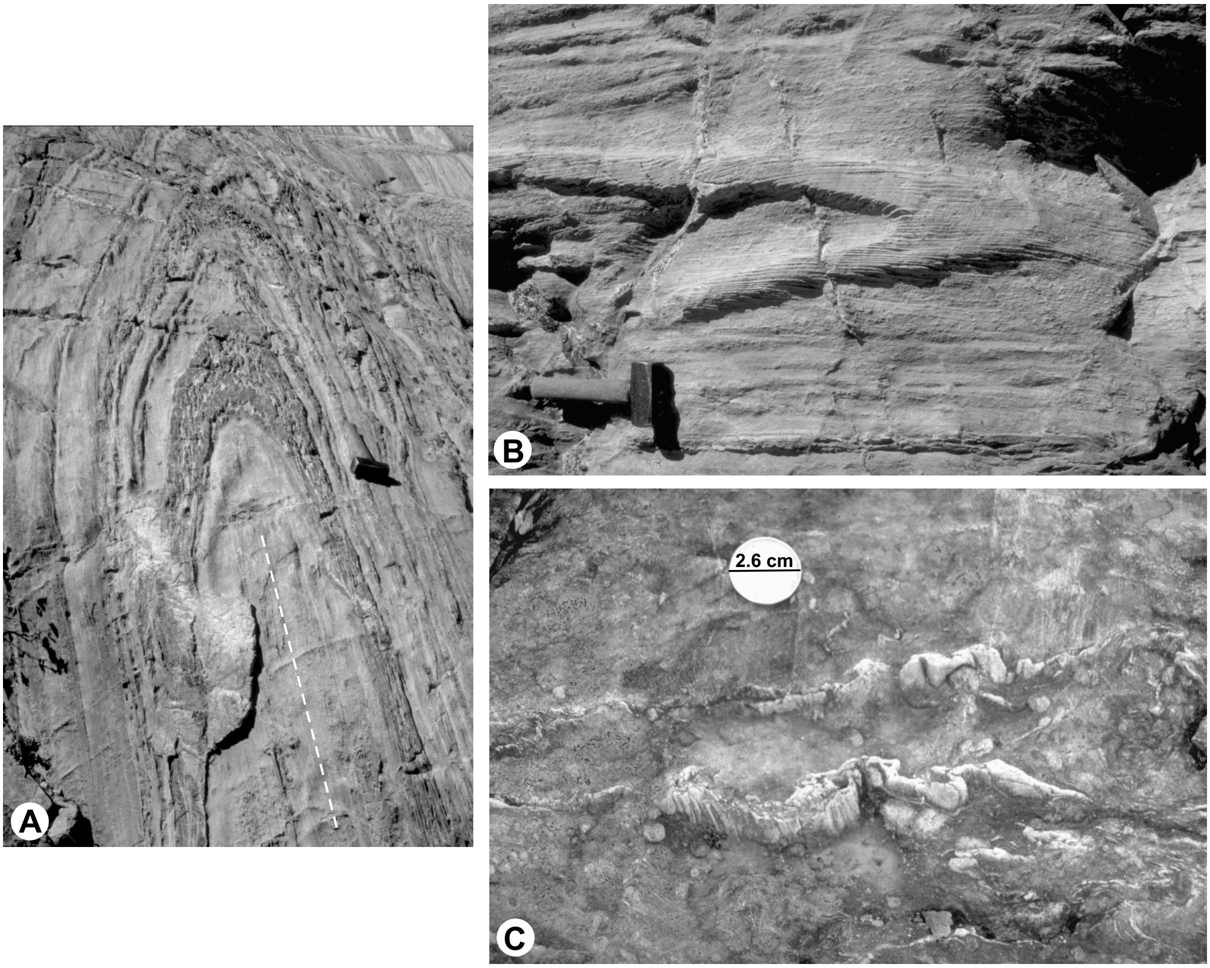

FIG. 15. A, B. Examples of F_2 folds. Note the well-developed axial planar foliation (S_2). Heritage Outcrop, Williams property. C. F_2 sheath folds with hinges subparallel to the L_2 stretching lineation. The geometry cannot be a result of overprinting because the "S" and "Z" folds share the same axial planar foliation (S_2). North side of Highway 17 near turnoff to the radio tower (or to the Hemlo station). All photographed surfaces are subhorizontal.

Moose Lake porphyry (unit AMLp) and the heterolithic conglomerate (unit Acg). Reversals in S_0 and S_2 relationships observed in the conglomerate support the presence of this F_2 fold. The axial plane of the fold strikes east-southeasterly. Drilling results indicate that the fold hinge, as defined by the folded conglomerate, plunges ~60° northwest (A. Guthrie, pers. commun., 1995).

Teck-Corona property fold: This fold is located in the Teck-Corona property (Fig. 3). The possibility of such a fold has been recognized by Guthrie (1984), Goad (1987) and Muir (1997). The results of the present mapping show that both the Moose Lake porphyry (unit AMLp) and the underlying calc-silicate-band–rich wacke (unit Acw) are repeated in a way that is consistent with the folding (Fig. 3). The quartz-porphyry exposed at the barren sulfide zone appears identical to the Moose Lake porphyry at the "A" zone pit of the Williams property (Fig. 17). Dating of zircons from the two parts shows that they have a similar age and are both distinct from other rocks in the area in that they contain inherited zircons of ~2800 Ma (Davis, 1998). A trenching program designed to test the interpretation of the fold confirmed the geometry. It clearly shows that the two porphyries merge at the interpreted location of the fold closure (Fig. 17; T1, T2, and T3 are the three trenches).

Moose Lake fold: The Moose Lake fold (Figs. 2, 3) is a newly recognized structure and is most important for interpreting the geologic setting of the Hemlo gold deposit. It is well established on the basis of repetition of lithologic units and structural observations (Fig. 18).

Lithologic units that are repeated by the fold, and which can be traced around the fold closure (either on surface or underground), include the hanging-wall and footwall sediments (unit Acw), the Moose Lake porphyry (unit AMLp), the barite horizon (coincident with the two ore zones), and the magnetite-band–rich layer at the base of the upper graywacke (unit Agwu) (Fig. 18). Structural observations support the presence of the fold; the angle between S_2 and the enveloping surface of F_2 folds or bedding (S_0) is high along the axial surface trace of the fold (Fig. 18; Fig. 6F, G) and low at the limbs. The presence of the fold is also indicated by younging direction reversal on the basis of field observations (Fig. 7A) and the logging of drill core (J. Clark, pers. commun., 1995).

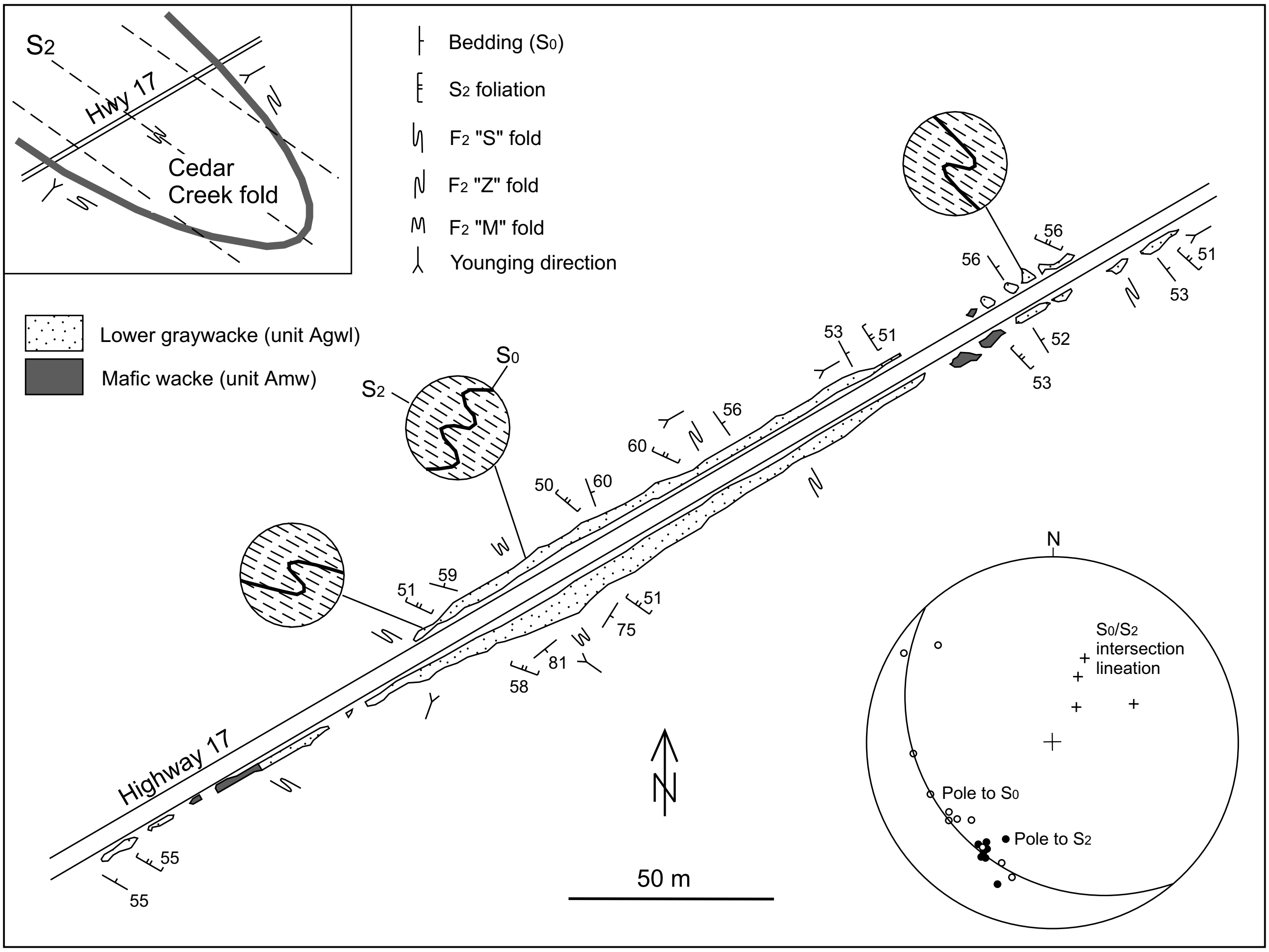

FIG. 16. Map of an outcrop along Highway 17 near Cedar Creek, showing structures related to the Cedar Creek fold. The inset on the upper left shows the location of the outcrop relative to the Cedar Creek fold, and that on the lower right is an equal-area lower-hemisphere projection of structural data from the outcrop.

The geometry of the Moose Lake fold is best depicted by the folded contact between the Moose Lake porphyry (unit AMLp) and the upper graywacke (unit Agwu). The fold closure defined by the contact is located under Moose Lake (Fig. 18), but its position is well constrained in underground workings (e.g., Fig. 19A, B). It plunges steeply northwest to a depth of ~650 m and then curves sharply toward the east and plunges shallowly (Fig. 20). Data indicate that the contact between the Moose Lake porphyry (unit AMLp) and the underlying metasediments (units Av and Acw) has a similar geometry (Fig. 20), although it is not as well constrained. Surface mapping shows that the contact closes by multiple parasitic folds in the west (Fig. 2), where drilling results indicate that the hinges plunge steeply to the northwest (B. Kusins, pers. commun., 1995). Drilling results at the Williams mine and the Golden Giant mine show that the Moose Lake porphyry bottoms out at depth where the hanging-wall and footwall sediments (unit Acw) join (e.g., Fig. 19B), indicating that the closure also turns toward the east to be shallowly plunging. The three-dimensional geometry of the Moose Lake fold is shown schematically in Fig. 20. Also shown is that the two ore zones at Hemlo coincide with the two limbs of the Moose Lake fold.

The Hemlo shear zone

G_2 deformation is most intense in the Hemlo shear zone, where mylonites are widespread (e.g., Fig. 21A). The shear zone is ~700 to 1,000 m wide in the study area. The southern boundary of the shear zone coincides with the southern contact of a sliver of metabasalt (amphibolite, unit Ab; Figs. 2, 3). The northern boundary is gradational. To the west of the “C” zone pit of the Williams mine, the shear zone strikes easterly. To the east of the pit, it strikes east-southeasterly. The following observations are related to the interpretation of the kinematics of the Hemlo shear zone.

1. The stretching lineation in the Hemlo shear zone plunges moderately to steeply to the northwest (Fig. 13). On horizontal surfaces, structures indicating sinistral shearing are well developed (Fig. 21B, C). However, on sections parallel to

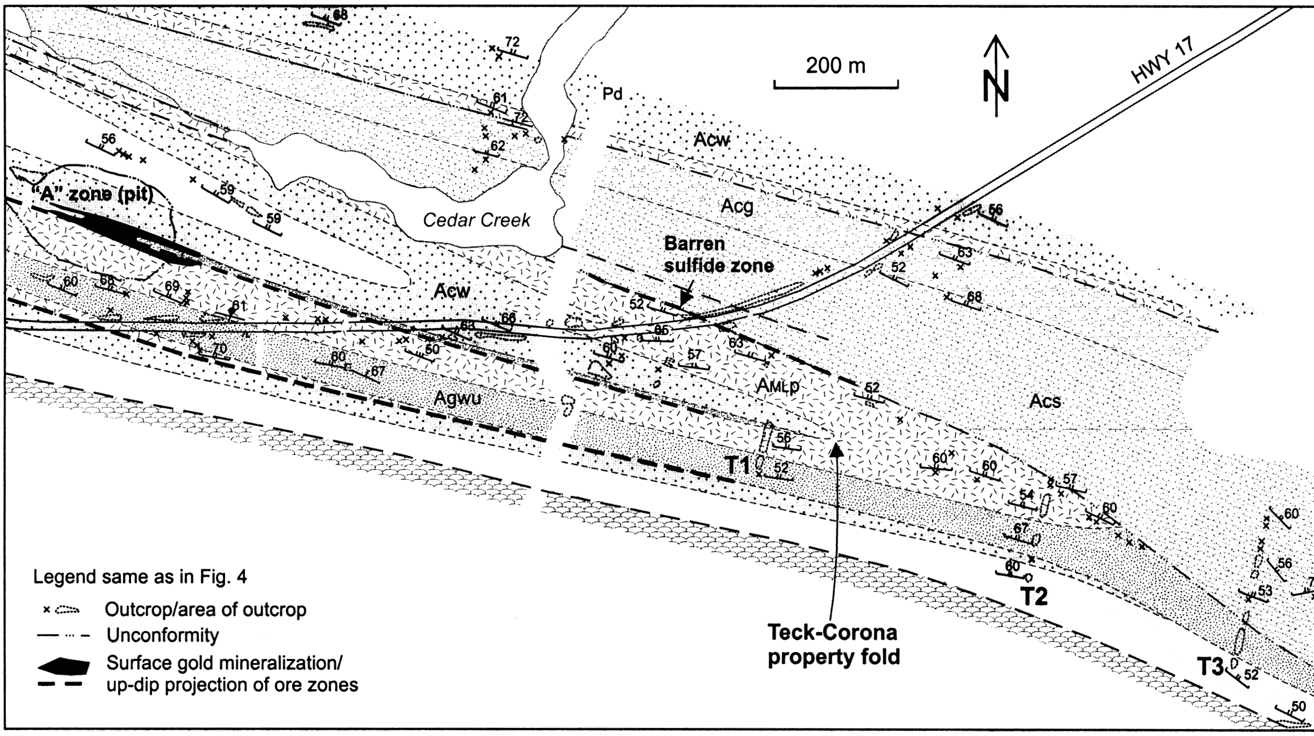

FIG. 17. Detailed map of part of the Teck-Corona property, showing the closure of the Teck-Corona property fold. T1, T2, and T3 are three trenches designed to test the fold closure. The quartz porphyries (unit AMLp) at the "A" zone pit and at trenches T1 and T2 occur along strike of one another and are all in contact with the upper graywacke (unit Agwu) to the south. They are thus lateral equivalents. The quartz porphyry at trench T2 is traced along strike into that at the barren sulfide zone and both porphyries are in contact with a cummingtonite schist (unit Acs) to the north. Therefore, all the porphyries are lateral equivalents and their spatial distribution indicates folding. The porphyry (AMLp) and the upper graywacke (Agwu) are unconformably overlain by a heterolithic conglomerate (unit Acg) and the cummingtonite schist (Acs). Legend same as in Fig. 4. Pd = diabase dike.

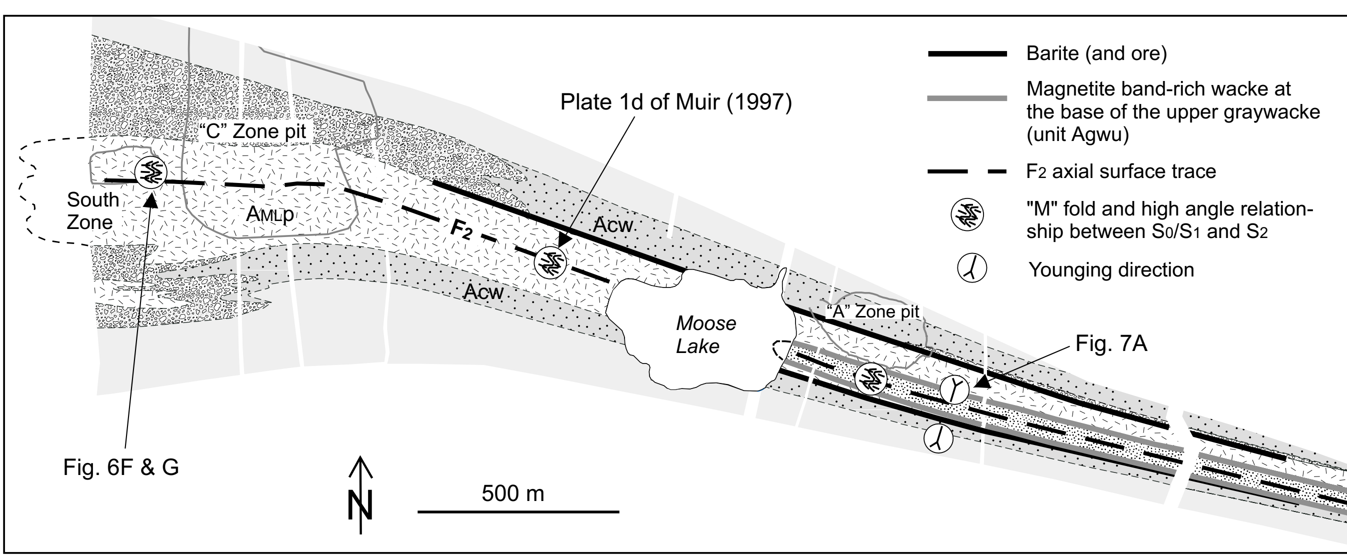

FIG. 18. Schematic diagram summarizing the major lines of evidence for the Moose Lake fold. Features illustrated in Fig. 6F, G and Fig. 7A, and in plate 1d of Muir (1997) are located for reference. See text for discussion. Legend same as in Fig. 4.

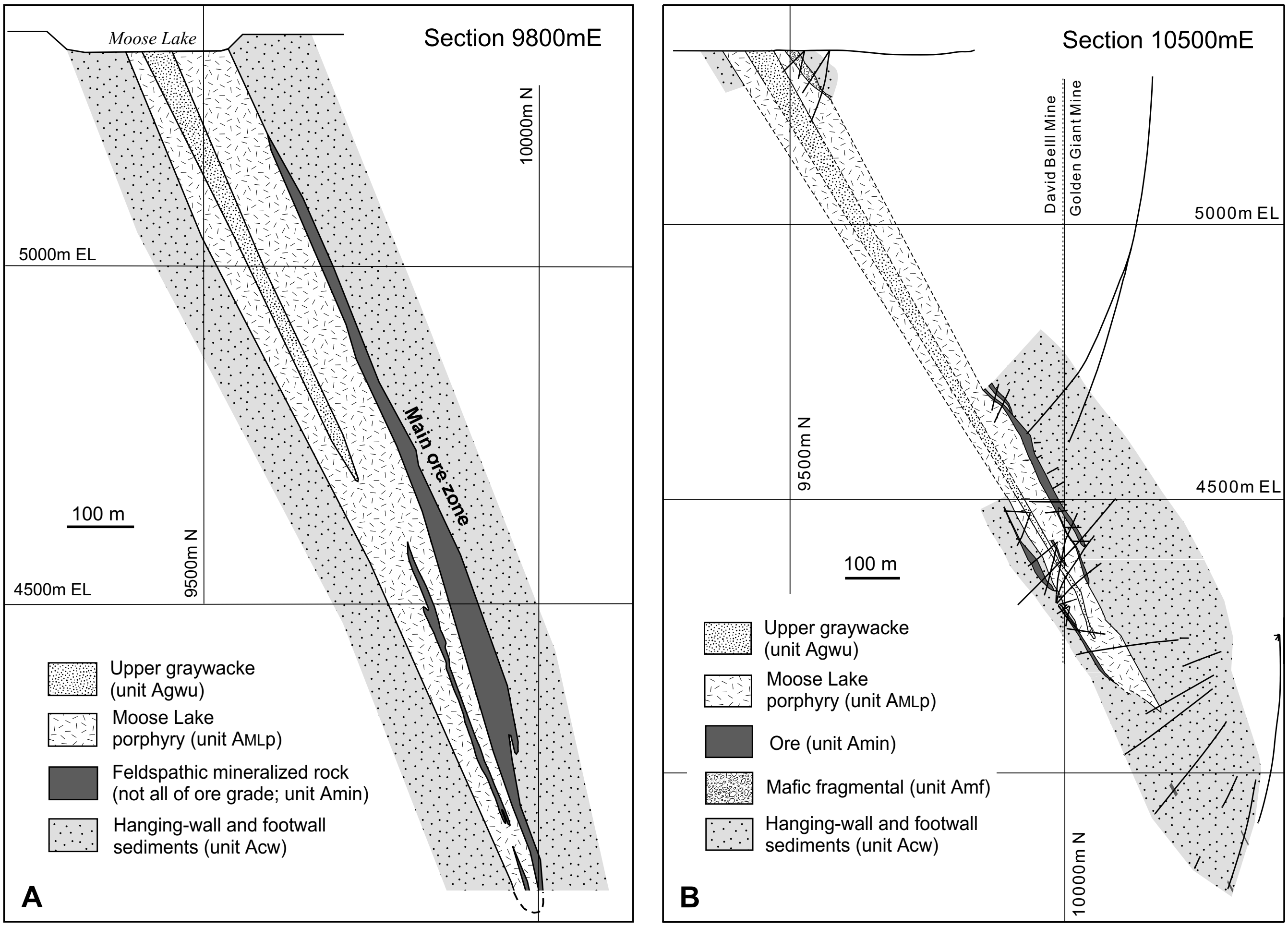

FIG. 19. A. Section 9800mE of the Williams mine, showing the F_2 fold closure in the contact between the Moose Lake porphyry (unit AMLp) and the upper graywacke (unit Agwu). Looking west. Simplified from a diagram of the Williams mine and modified on the basis of compilation of detailed sections and plans of the mine. B. Section 10500mE of the David Bell/Golden Giant mine, showing the F_2 fold closures in the contact between the Moose Lake porphyry (unit AMLp) and the upper graywacke (unit Agwu), and in the contact between the Moose Lake porphyry and the hanging-wall and footwall sediments (unit Acw). The thin lines, mostly oriented from lower left to upper right, are drill holes. Looking west. Modified from a diagram compiled by R.H. Sutcliffe and G. Shore (pers. commun., 1997). Note that the mine grid northings and eastings are shown in Figure 3.

the lineation, no evidence for consistent shear sense has been recognized. Away from the Hemlo shear zone, the lineation is not as well developed. Where observed, it tends to be shallower to subhorizontal.

2. Clasts in the fragmental rocks in the Hemlo area are good finite strain markers. The finite strain recorded is different west and east of the “C” zone pit. West of the pit, the finite strain is prolate or the strain ellipsoid is close to cigar shaped. The clasts are strongly elongated on sections parallel to the lineation but only weakly elongated on sections perpendicular to the lineation (Fig. 14A). In contrast, to the east of the “C” zone pit, where the shear zone strikes east-southeasterly, the finite strain is oblate or the stain ellipsoid is close to pancake shaped. The clasts are only slightly more elongated on sections parallel to the lineation than on sections perpendicular to the lineation. The latter is best illustrated by the shape of the clasts in the mafic fragmental unit underground. Therefore, the lineation is better developed west of the “C” zone pit than east of the pit.

The structural association described above indicates that the Hemlo shear zone may be a sinistral transpressional zone. Transpressional shear zones contain a transcurrent movement component (parallel to the zone boundary) and a compressional component (normal to the zone boundary). Recent studies indicate that they are common in nature. In transpressional shear zones the stretching lineation may be very steep even though the strike-slip movement component may be dominant, especially where the strain is high (e.g., Sanderson and Marchini, 1984; Lin et al., 1998). In such shear zones, evidence for structures related to noncoaxial shear (e.g., shear bands and en echelon quartz veins of Fig. 21B, C) are best developed on horizontal surfaces although the stretching lineation may be very steep, as is the case in the Hemlo shear zone. Sinistral transpression would lead to a bigger compressional component and stronger deformation in the segment of the Hemlo shear zone that strikes east-southeasterly.

As described above, the F_2 folds generally have “S” asymmetry, both at the outcrop and the camp scales. The axial

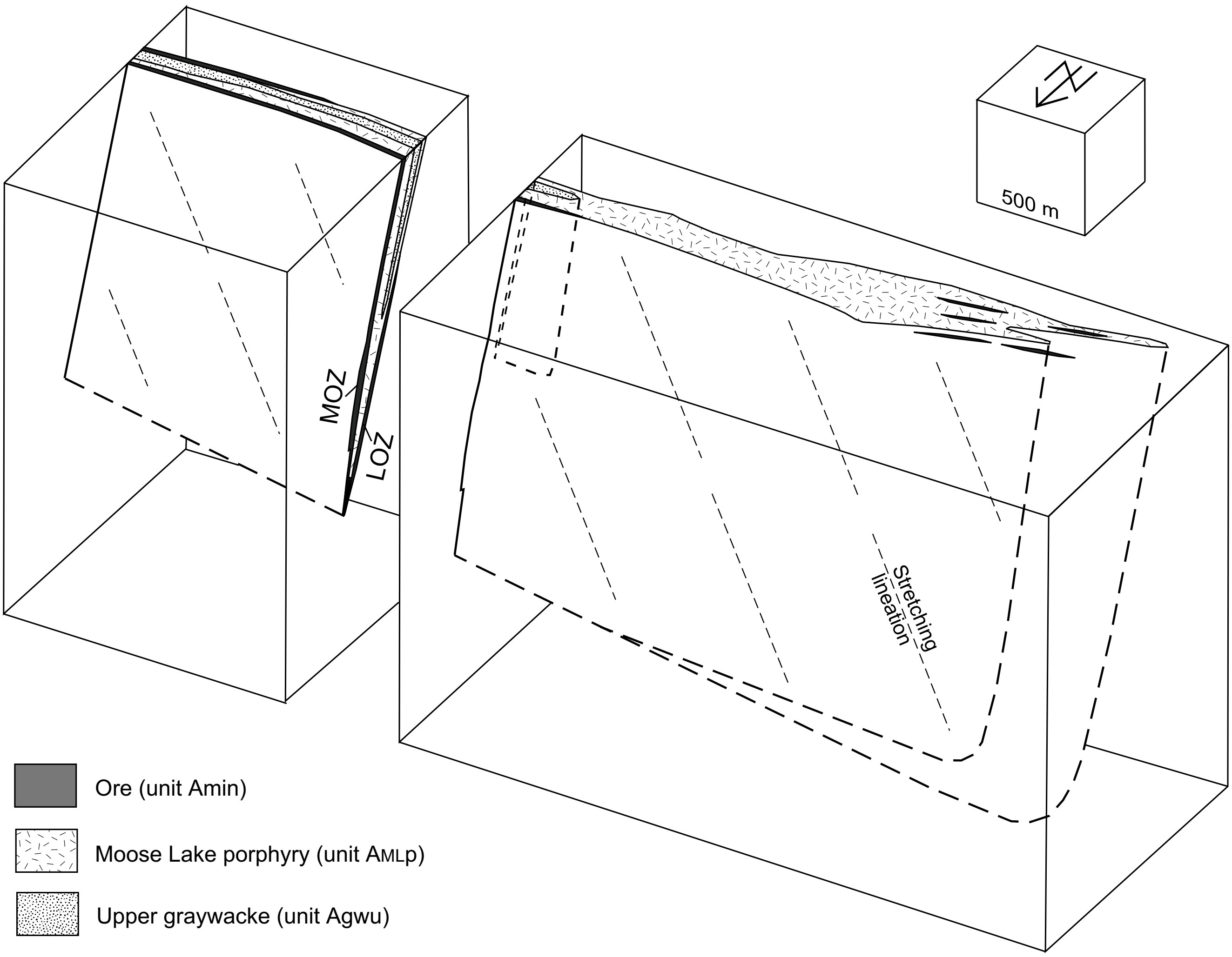

Fig. 20. Orthographic projection schematically showing the three-dimensional geometry of the Moose Lake fold. Looking down toward southeast. Note that the two ore zones are spatially associated with the folded stratigraphically lower contact of the Moose Lake porphyry (unit AMLp). MOZ = main ore zone; LOZ = lower ore zone.

planes of the folds and the associated axial planar foliation (S_2) are subparallel to the Hemlo shear zone near the center of the shear zone and become more oblique (clockwise) to it away from the center. The axial plane of the Moose Lake fold, which is located near the center of the shear zone, strikes ~105°, those of the Teck-Corona property and the Williams property folds ~115°, and that of the Cedar Creek fold ~130° (Fig. 2). These folds are spatially associated with, and are probably kinematically related to, the east-southeast–trending segment of the Hemlo shear zone (Fig. 2). They are interpreted as drag folds associated with sinistral movement along the shear zone.

Third-generation (G_3) structures

G_3 structures are divided into two subgroups, G_{3a} and G_{3b}. F_{3a} folds are widespread in and south of the Hemlo shear zone. They are also common underground in the mines. The folds are generally open to tight with a locally well developed axial planar crenulation cleavage (Fig. 22A, B). Their hinges plunge shallowly to moderately to the east-northeast. They have a consistent "Z" asymmetry looking down plunge. S-C structures associated with the G_{3a} deformation are observed underground at several localities. The S-C structures, together with the fold vergence, indicate north-over-south sense of shear with a dextral strike slip component.

F_{3b} folds occur in and near the Hemlo shear zone. They are generally open with a locally developed axial planar crenulation cleavage (Fig. 22C, D). Their hinges plunge steeply to the northeast. They have a consistent "Z" asymmetry looking down plunge. Locally, a subhorizontal stretching lineation associated with G_{3b} deformation is well developed (Fig. 22E). The "Z" folds, the geometry of deformed veins (Fig. 22F), and S-C structures all indicate that the G_{3b} deformation was associated with dextral shearing.

Many F_{3b} folds are spatially associated with boudinaged feldspar porphyry dikes (e.g., Fig. 21C and 22C). The geometry indicates that the dikes were most likely boudinaged before the F_{3b} folding, probably during G_2 deformation (e.g., Fig. 21C), and the location of the boudin necks controlled the location of the F_{3b} folds.

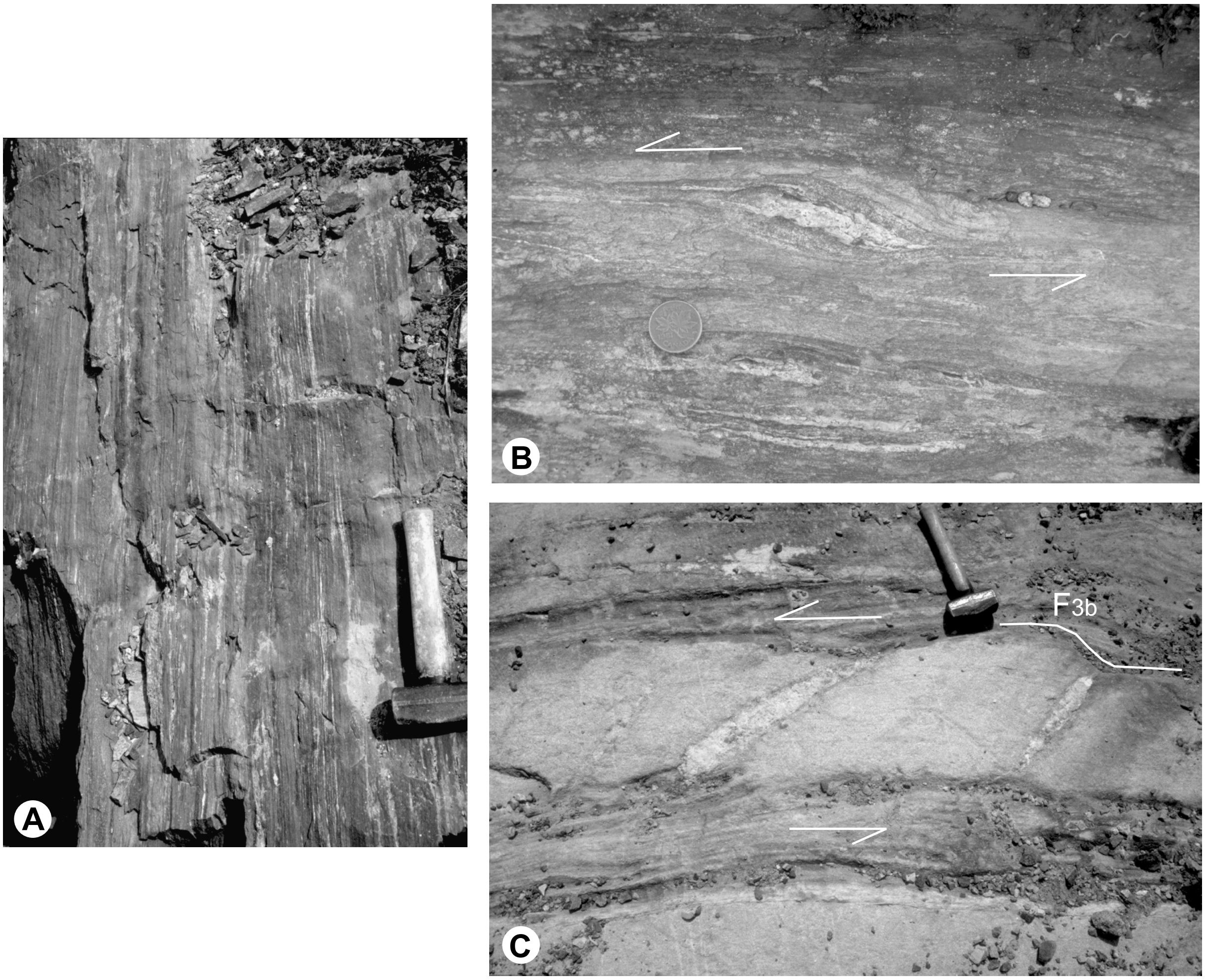

FIG. 21. A. Strongly sheared mafic rocks (mafic mylonite) in the Hemlo shear zone. Subhorizontal surface. South side of Highway 17 near the radio tower. B. Shear bands indicating sinistral shearing in the Hemlo shear zone. Subhorizontal surface. On the east side of the road from the Golden Giant mine tailings pond to the North zone pit. C. En echelon quartz veins in a feldspar porphyry dike indicating sinistral shearing in the Hemlo shear zone. The dike was more competent than the country rock and was boudinaged during G_2 deformation. Note the open "Z" fold (F_{3b}) in the dike spatially associated with the boudin neck on the right. Horizontal surface. Near the west shore of Moose Lake, in the Williams property.

F_{3a} and F_{3b} folds are very similar in style, and no overprinting relationship between the two has been observed. They are separated on the basis of difference in hinge orientations. Therefore, the designation of F_{3a} or F_{3b} does not necessarily reflect structural sequence. The dip slip movement associated with G_{3a} and the strike slip associated with G_{3b} may represent two separate deformation events, as suggested by Michibayashi (1995; his F_2 and F_3, respectively). It is also possible that the dip slip and strike slip movements are kinematically related to a single oblique shearing event. Recent studies of shear zone deformation show that regional oblique shearing is commonly accommodated by separate zones of strike slip and dip slip, a phenomenon called slip partitioning (see Lin et al., 1999, and references therein). It should be noted that whether or not the G_{3a} and G_{3b} deformation are related to a single deformation event does not affect the interpretation of the genesis of the Hemlo deposit because the main mineralization event occurred before G_{3a} or G_{3b} deformation (see below).

Fourth-generation (G_4) structures

Kinks of "S" asymmetry are observed locally in the map area. The kink bands generally strike north-northwesterly. The hinges plunge steeply. They are observed to overprint S_2 foliation, but no overprinting relationship has been observed between G_3 and G_4 structures. The kinks are believed to be the youngest brittle-ductile structures in the area on the basis of their style.

Brittle faulting

The youngest structures in the Hemlo area are brittle faults. They occur at various scales and in different orientations, and they have quite different kinematics. They may also have very different ages. As examples, the two most common groups are described here.

One common group of brittle faults is parallel to the S_2 foliation. The faults range from outcrop scale to map scale. The

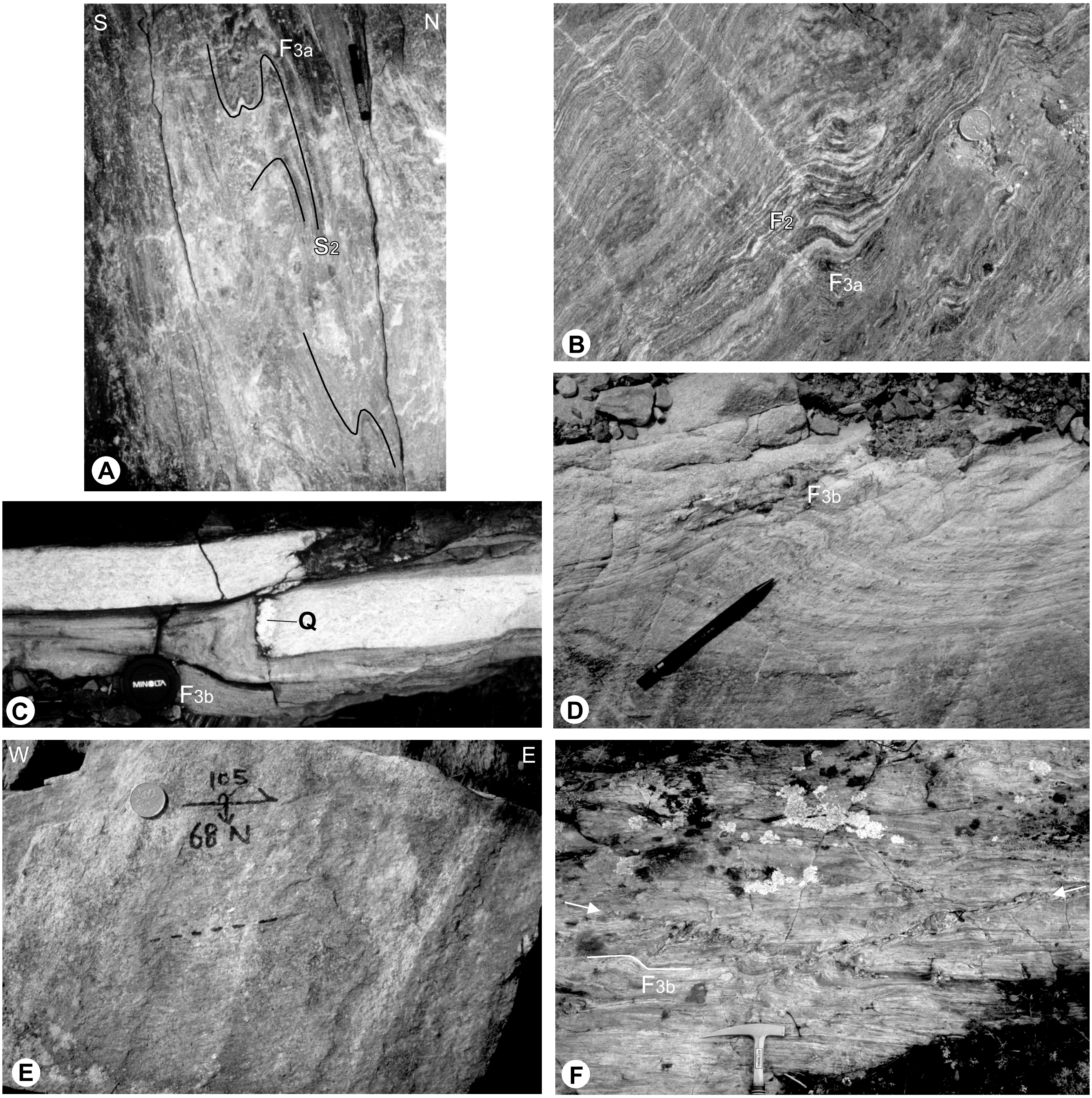

FIG. 22. A. Examples of F_{3a} folds in foliated Moose Lake porphyry. The folds deform an earlier foliation (S_2). Subvertical surface. Underground in the Golden Giant mine. B. F_{3a} folds overprint F_2 folds in a metabasalt. Subhorizontal surface. South of the Hemlo shear zone. C, D. Examples of F_{3b} folds. The folds are associated with boudinaged feldspar porphyry dikes. Q = quartz vein in boudin neck. The folds in D have a well-developed axial planar crenulation cleavage (parallel to the pencil). Subhorizontal surfaces. C is on the south side of Highway 17, south of the "A" zone pit. D is from within the Williams property, near west shore of Moose Lake. E. Subhorizontal stretching lineation associated with G_{3b} deformation. Steeply dipping surface. North side of Highway 17 in the Williams property. F. Structural association indicating dextral shearing associated with G_{3b} deformation: the F_{3b} folds are of "Z" asymmetry; a quartz vein trending clockwise to the foliation, indicated by (and parallel to) the arrow on the left, is folded by F_{3b}; and a quartz vein trending anticlockwise to the foliation, indicated by the arrow on the right, is boudinaged. The structural association can be produced only by dextral shearing. Subhorizontal surface. North side of Highway 17, west of the Williams mine.

outcrop-scale faults are indicated by zones of cataclasite, fault breccia, and local pseudotachylites. Map-scale faults commonly occur along lithologic contacts and include the Hemlo fault and the fault at the northern contact of the metaconglomerate (unit Amcg) south of the Hemlo fault (Fig. 3). The latter dextrally offsets Proterozoic diabase dikes (Fig. 3). The Hemlo fault occurs at the northern contact of the metabasalt (amphibolite, unit Ab) at the southern edge of the Hemlo shear zone. The fault contact is indicated by a chlorite zone a few tens of centimeters wide that was observed on the surface, underground in the Williams mine, and in drill cores. Diabase dikes do not appear to be offset by the fault zone; either the diabase is postfaulting or the horizontal movement along the fault is negligible.

The other common group of brittle faults strike southeasterly. These faults have a consistent dextral sense of shear. They are observed on the surface and are abundant underground in the David Bell mine, where they commonly offset the main ore zone.

Deformation of the orebody and structures at the orebody scale

Underground (mesoscopic) observations: Detailed underground work shows that the orebodies are affected by G_2 and later generations of deformation. Both G_2 and G_3 structures are widespread in the ore. Two examples of F_2 folds that affect the ore are shown in Fig. 10E, F. In the first example, a molybdenite seam in a feldspathic ore is deformed by an isoclinal F_2 fold, and in the second example, a pyrite vein is deformed by a tight F_2 fold. Both folds have well-developed S_2 axial planar foliation, and the pyrite vein is partly transposed into the S_2 foliation.

Both the feldspathic and sericitic ore have generally well-developed S_2 foliation. The foliation is defined by white mica and by compositional layering (e.g., pyrite bands in Fig. 10C) and molybdenite seams. F_3 folds that overprint the S_2 foliation are widespread in the orebody, particularly F_{3a} folds.

Results of compilation and macroscopic (orebody-scale) structures: Geologists at the three mines have mapped all levels in detail and have constructed numerous sections on the basis of drilling results and underground mapping. Major efforts were made in this study to compile this data. The reader is referred to Lin (2001) for representative level plans and sections compiled from the data of the Williams and Golden Giant mines. Block diagrams showing the geometry of the main ore zone are given in Fig. 23A, B. Because there is a level plan about every 25 m and a section every 10 to 25 m, the geometry is very well constrained. The diagrams show that the main ore zone is folded by F_2 at the orebody scale. The orebody is thickened by as much as four times by folding, and the variation in thickness of the orebody at Hemlo is to a large degree due to folding. The folds are strongly noncylindrical and have the geometry of protosheath folds (Fig. 23A).

Summary of structure and restoration of predeformation geometry

Four generations of ductile structures (G_1 to G_4) as well as brittle faulting are recognized in the Hemlo area. G_1 is recognized on the basis of locally preserved structures that are overprinted by G_2. G_1 and G_2 are possibly related to a single progressive deformation episode. G_2 deformation is the strongest, and the geometry of the Hemlo camp is dominated by macroscopic (map-scale) "S"-shaped F_2 folds. The two ore zones at Hemlo are spatially associated with the two limbs of a newly recognized camp-scale F_2 fold, the Moose Lake fold; the orebody is folded by F_2 at the outcrop, the mine, and possibly the camp scale. The G_2 deformation is strongest in the Hemlo shear zone, interpreted to be a sinistral transpressional zone. The Hemlo gold deposit is hosted in the shear zone, mainly in the segment that trends east-southeasterly where deformation is stronger. G_3 structures are probably related to oblique dextral shearing. G_4 deformation is minor and produced only local kinks.

With elucidation of the three-dimensional geometry and the deformation history, the predeformation geometry in the immediate mine area is qualitatively restored. The result is shown schematically in Fig. 24. It shows that the zone of alteration and mineralization is associated with the stratigraphically lower contact of the Moose Lake porphyry where the mafic fragmental rock and the barite horizon are located. Note that this does not necessarily mean that the alteration and mineralization have to have occurred before folding (see below).

Age Relationships

Major age relationships are summarized in Fig. 25, and the most important ones are discussed below.

Intrusion of aplite dikes versus deformation, alteration, and mineralization

Aplite dikes are observed underground in both the main and lower ore zones. They are folded by F_2 folds (Fig. 26A) with axial planar foliation (S_2) defined by white mica (Fig. 26B). Their intrusion was thus pre-G_2 to early syn-G_2 deformation. They are altered (Fig. 26B) and mineralized. A sample from the dike shown in Fig. 26A yielded a gold assay of 5.16 g/t and a sample from another location 5.07 g/t. The intrusion of the aplite dikes therefore predated at least a significant part of alteration and mineralization at Hemlo. Robert and Poulsen (1997) suggested that the aplite dike is postore on the basis of observations that the aplite has a style of mineralization different from, and contains less pyrite than, the wall rock. However, these differences can be explained by difference in protolith composition and texture of the aplite from that of the wall rock. More detailed work on the nature of the alteration and mineralization of these dikes may help to better constrain the timing relationship between the intrusion of the dikes and the alteration and mineralization. Zircons from such a dike yielded an U-Pb age of 2677.2 ± 1.5 Ma (Davis, 1998).

Intrusion of feldspar porphyry dikes versus deformation, alteration, and mineralization

Feldspar porphyry dikes are common in the area. They range from <10 cm to ~20 m wide. They consist of two major groups, dark-gray porphyry dikes with coarse-grained feldspar phenocrysts (the "popcorn porphyry" dikes; Fig. 27A, B) and light- to medium-gray porphyry dikes with medium-grained feldspar phenocrysts (Fig. 27C). A latter dike has yielded an U-Pb zircon age of 2677.5 ± 1.3 Ma (Davis, 1998).

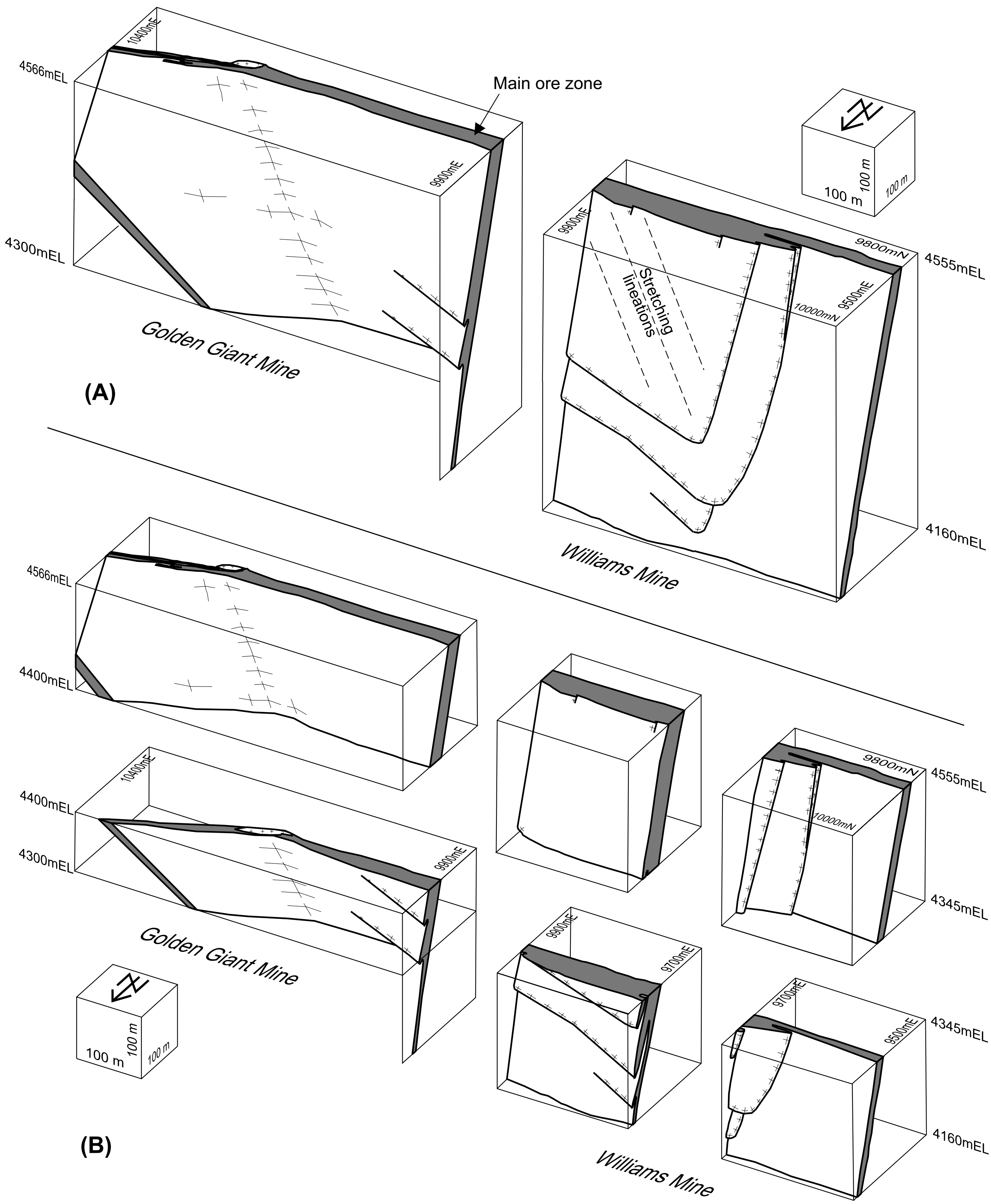

FIG. 23. A, B. Orthographic projection of the Hemlo main ore zone on the basis of compilation of level plans and sections from the Williams mine and the Golden Giant mine. A and B show the geometry of the same orebody. Looking down toward southeast. Note that the mine grid northings and eastings are shown in Figure 3.

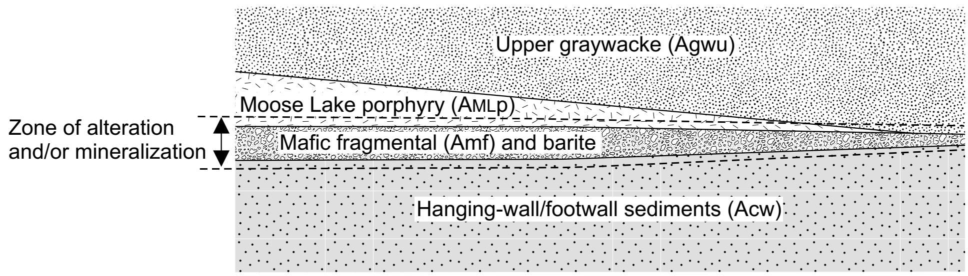

FIG. 24. Schematic cross section showing the restored prefolding geometry of the Hemlo camp. Note that the zone of alteration and mineralization is spatially associated with the lower contact of the Moose Lake porphyry and with the mafic fragmental unit and a barite horizon.

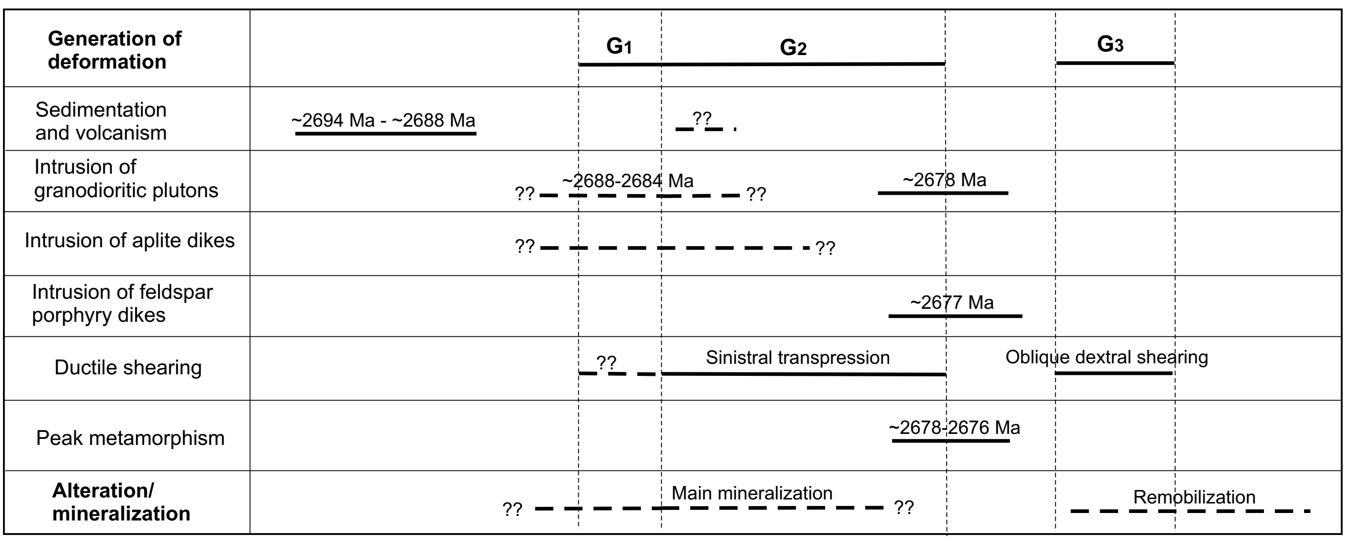

FIG. 25. Diagram summarizing the major age relationships at Hemlo (see text for discussion).

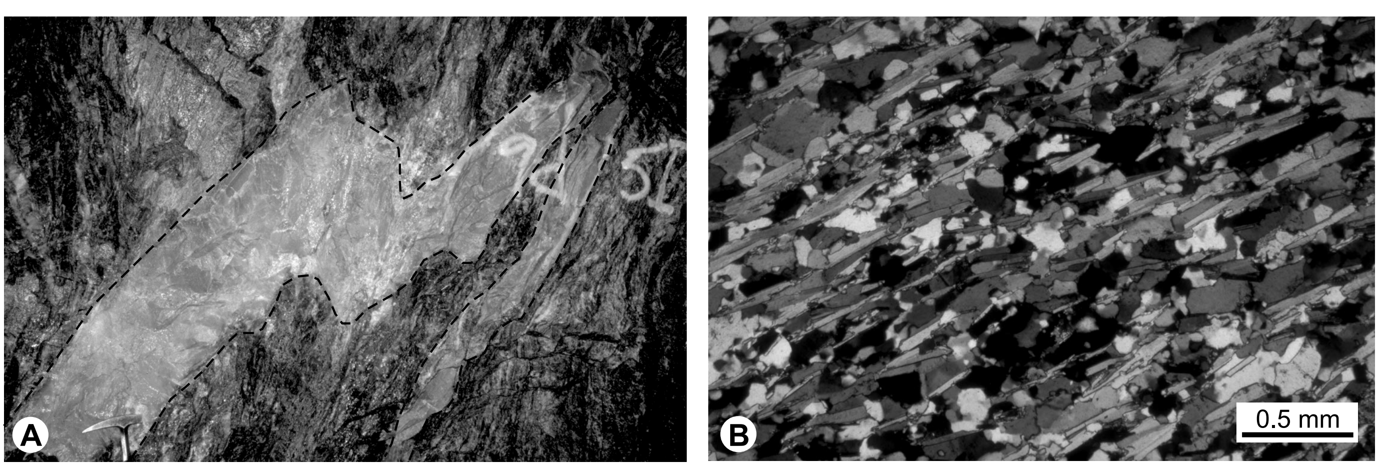

FIG. 26. A. An aplite dike in the ore is folded by F_2 with axial planar foliation. It is altered and mineralized. David Bell mine lower ore zone. B. Photomicrograph of the aplite dike shown in A. It is altered (sericitized) and metamorphosed. The white mica defines a foliation (S_2) that is axial planar to the F_2 fold shown in A. Crossed nicols.

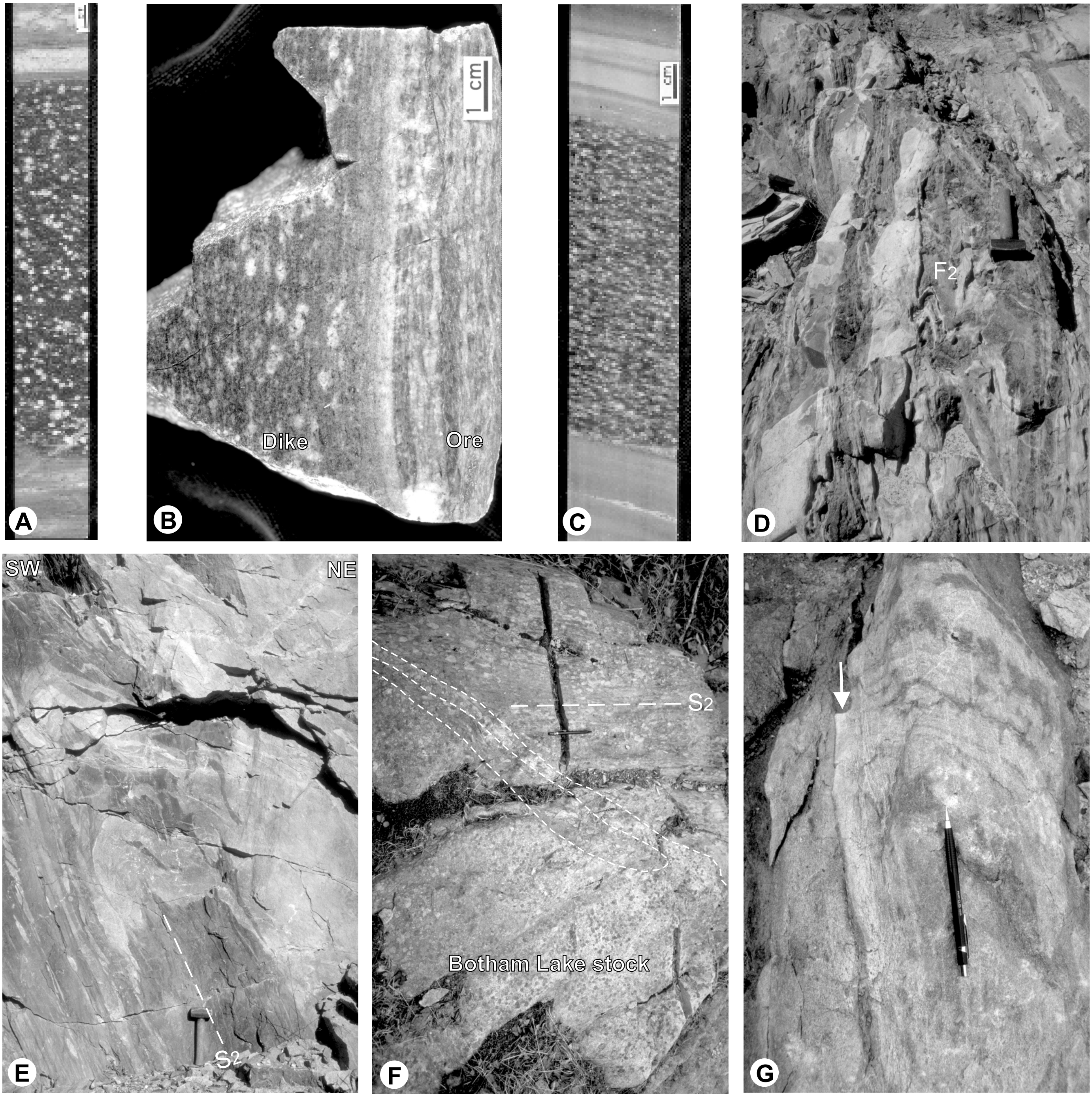

FIG. 27. A, B, C. Three examples of feldspar porphyry dikes cutting ore and/or alteration zones. Shown in A and B are "popcorn porphyry" dikes. The dikes are generally not altered or mineralized. Locally, they show evidence of alteration near the margins, as in B. D. Feldspar porphyry dikes subparallel to S_2, boudinaged during G_2 deformation and bearing a weak S_2 foliation. Note that they are not folded by the F_2 fold near the center of the photo. Subhorizontal surface. Heritage Outcrop, Williams property. E. Near the western margin of the Cedar Lake pluton, apophyses of granodiorite into the country rocks are folded by F_2 with S_2 as axial planar foliation. Subvertical surface. F. At the northern margin of the Botham Lake stock, apophyses of granodiorite into the country rocks cut the S_2 foliation and are weakly folded by F_2. Subhorizontal surface. G. An altered rock is folded by F_2 with additional alteration zones parallel to the axial plane (S_2) of the fold. One such alteration zone is indicated by the white arrow. Subhorizontal surface. A trench west of the North zone pit.

The feldspar porphyry dikes occur dominantly in G_2 shear zones (e.g., the Hemlo shear zone and the shear zone shown in Fig. 5B). They are generally subparallel to S_2 including in the hinge areas of F_2 folds (Figs. 27D, 28). They were boudinaged during G_2 deformation (Figs. 21C, 27D) and bear a weak to clear S_2 foliation (Fig. 27A-C). They are folded by F_3 folds (Figs. 21C, 22C) but are only locally openly folded by F_2, although F_2 folds in bedding are generally very tight to isoclinal. These observations indicate that the dikes intruded late during G_2.

The feldspar porphyry dikes cut the ore and altered rocks (Fig. 27A-C) and are in general not altered or mineralized, indicating that their intrusion postdated alteration and mineralization. Detailed examination shows that some dikes in the mineralized and/or altered rocks are altered and/or mineralized near the margins (e.g., Fig. 27B). Either the latter dikes intruded at the late stage of alteration and mineralization, or the observed alteration and mineralization along their margins was related to later remobilization.

Intrusion of granodioritic plutons versus deformation

Pukaskwa Intrusive Complex: Granodiorite in the northern margin of the Pukaskwa complex (U-Pb zircon age ~2719 Ma) is strongly deformed and bears a strong foliation (S_1) that is transposed by F_2 folding into parallelism to S_2 foliation (Fig. 12C). The intrusion of the granodiorite must have occurred before G_2 deformation.

Cedar Lake pluton: Granodiorite of this pluton (U-Pb zircon age ~2688 Ma) shows weak but penetrative G_2-related deformation. The S_2 foliation in the country rocks is parallel to the margin of the pluton. Near the western margin of the pluton, apophyses of the granodiorite into the country rocks are folded by F_2 folds with an S_2 axial planar foliation (Fig. 27E). These structures indicate that the intrusion of the pluton predated at least a major part of the G_2 deformation (i.e., was pre-G_2 to early syn-G_2).

Botham Lake stock: The Botham Lake stock consists of two small feldspar porphyritic intrusions (Fig. 2). It is elongated subparallel to the S_2 foliation and is massive to weakly foliated. Apophyses of the granodiorite into the country rocks cut the S_2 foliation and are weakly folded by F_2 (Fig. 27F). These indicate that intrusion of the granodiorite occurred late during G_2 deformation.

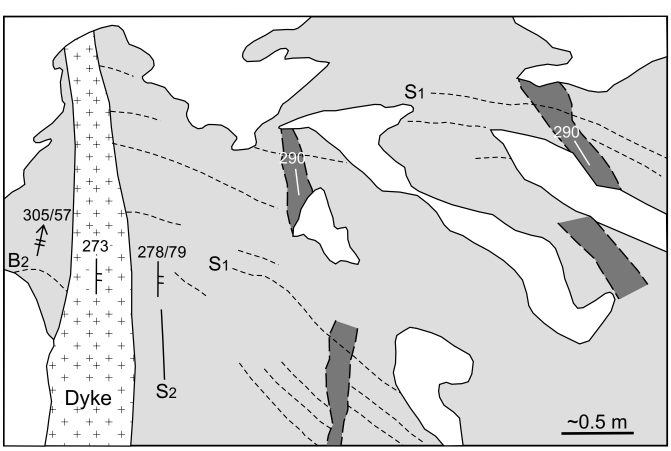

FIG. 28. Sketch of a photo (plate 10a of Muir, 1997), showing a feldspar porphyry dike subparallel to the axial plane (S_2) of F_2 folds and bearing a weak S_2 foliation. The dike is interpreted to have intruded late during G_2 deformation. Note zones of intense potassic alteration (dark gray) parallel to S_2 foliation. The alteration zones are subparallel and have a strike of ~290°, as indicated. The rocks have elevated Au and Mo values, and the intense alteration zones are enriched in potassium (5.12% K_2O within versus 2.75% K_2O outside the intense alteration zones; Muir, 1997). Subhorizontal surface. Looking down toward the west.

Peak metamorphism versus deformation

Peak metamorphism in the immediate mine area reached middle amphibolite facies (e.g., Burk et al., 1986; Kuhns et al., 1994; Powell et al., 1999). Microscopic observations indicate that peak metamorphism occurred late during G_2 to after G_2 deformation. For example, in garnet-hornblende metabasite, inclusion trails in both garnet and hornblende porphyroblasts are straight to curved and are continuous with S_2 in the matrix (Fig. 29A, B), indicating that these minerals grew late during G_2 to after G_2 deformation. Peak metamorphism must have occurred before G_3 deformation because foliation defined by peak metamorphic minerals is folded by F_3 folds.

Alteration and mineralization versus deformation

Key observations that constrain the age relationship of alteration and mineralization to deformation include the following:

1. The ore is in general strongly deformed, especially in the main and lower zones. It is folded by F_2 folds (at outcrop, orebody, and possibly camp scales), and exhibits a generally strong S_2 foliation.
2. The ore and altered rocks are cut by feldspar porphyry dikes that were intruded late during G_2 deformation.
3. Feldspathic ore is in general less deformed than the sericitic ore, indicating that alteration mineral assemblages controlled the strain distribution.
4. Sericite and green mica occur parallel to S_2 foliation, indicating that the minerals' growth was controlled by G_2 structures; either the alteration took place during G_2 deformation, or it took place before G_2 and the minerals recrystallized during G_2.

These observations indicate that the alteration and mineralization occurred before G_2 and/or early during G_2 deformation. The following observations and interpretations support alteration and mineralization early during G_2. Whether it had started earlier than G_2 is unknown.

1. At the outcrop scale, zones of potassic alteration and mineralization occur parallel to the axial plane in the hinge area of F_2 folds (Figs. 27G, 28). Such a spatial association indicates that this alteration and mineralization could not have occurred before F_2 folding. A similar spatial association is also observed at the mine scale, in the hinge area of the Moose Lake fold (e.g., the "C" zone and the bottom of the "B" zone of the Williams mine), where numerous ore lenses occur subparallel to the axial surface (S_2) (Figs. 3, 19A).
2. The Hemlo gold deposit is spatially closely associated with the Hemlo shear zone, a G_2 shear zone, and especially

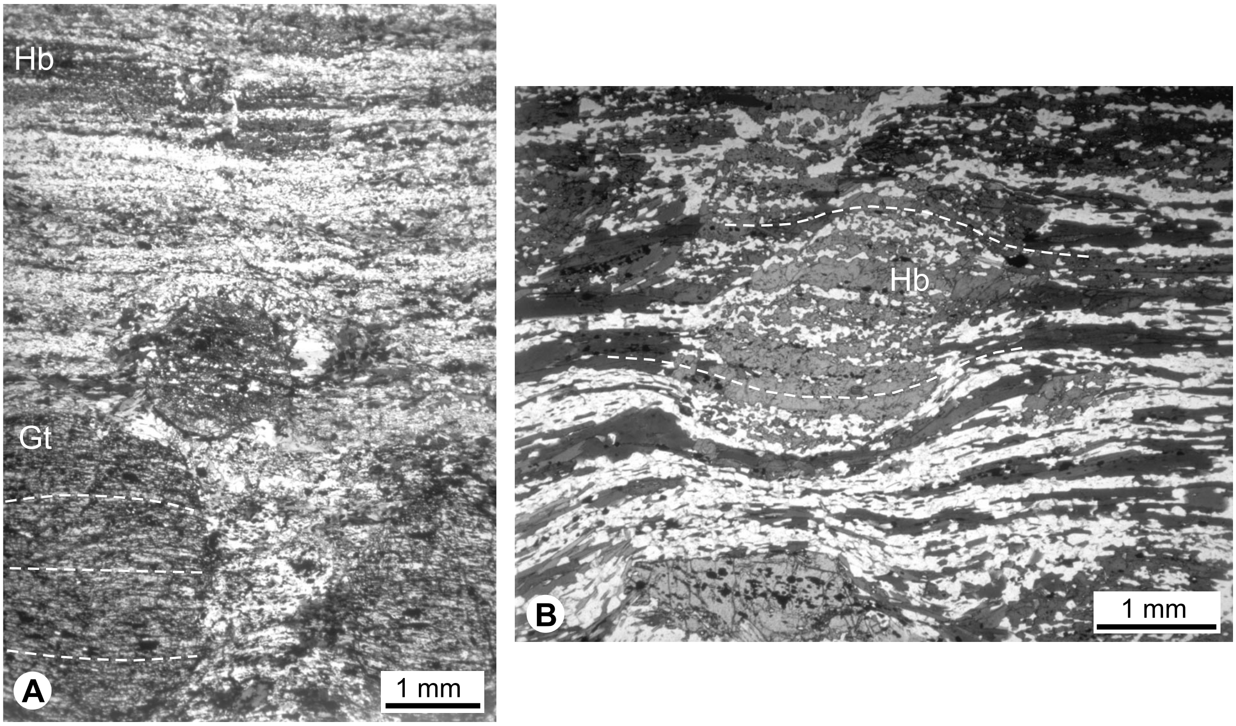

FIG. 29. A, B. Photomicrographs of a garnet (Gt)-hornblende (Hb) metabasite. The garnet and hornblende porphyroblasts contain inclusion trails that are continuous with the S_2 foliation in the matrix. The inclusion trails in the two garnet porphyroblasts at the lower edge of photo A and in the big hornblende porphyroblast in the center of photo B are straight in the middle and curved toward the upper and lower margins. The inclusion trails in the hornblende porphyroblasts near the upper edge of photo A are straight. Straight inclusion trails are also present in garnet porphyroblasts in the same thin section. These geometries indicate that the porphyroblasts grew late syn-G_2 to post-G_2 deformation. Plain polarized light. Near east shore of Botham Lake.

the east-southeast–trending segment of the shear zone. Such a spatial association, if not a coincidence, indicates that the location of mineralization was controlled by the geometry of the Hemlo shear zone.

Alteration and mineralization versus metamorphism

Because peak metamorphism occurred late during G_2 to after G_2 deformation and alteration and mineralization before G_2 or early during G_2 deformation, the alteration and mineralization must have taken place before peak metamorphism. This conclusion is supported by microscope observations that show that the altered and mineralized rocks have typical metamorphic texture (e.g., Fig. 6A), and it is consistent with that of most previous workers (e.g., Burk et al., 1986; Kuhns et al., 1994; Muir, 1997; Powell and Pattison, 1997).

The conclusion that mineralization at Hemlo took place before peak metamorphism may appear inconsistent with the presence of low- to moderate-temperature sulfide minerals, such as realgar, cinnabar, and stibnite, in the ore zones; the estimated peak metamorphic temperature of ~600°C exceeds the melting temperatures of these minerals (Powell and Pattison, 1997 and references therein). However, Powell and Pattison (1997) concluded that these minerals developed through a sequence of exsolution events during postpeak metamorphic cooling, which is consistent with the observation that these minerals are most commonly associated with quartz veins that cut the S_2 foliation. They suggest that Sb, As, and Hg were introduced prior to or during peak metamorphism and were incorporated into (unspecified) high-temperature antimonian sulfosalts during peak metamorphism.

Emplacement of the Moose Lake porphyry versus alteration and mineralization at the barren sulfide zone

In the barren sulfide zone (Figs. 3, 17), rocks are altered (sericitic and feldspathic alteration) and mineralized (pyrite and Au). The alteration and mineralization affects the cummingtonite schist (unit Acs). The cummingtonite schist lies stratigraphically above the heterolithic conglomerate and graywacke (unit Acg) that in turns lies (probably unconformably) on, and contains clasts derived from the Moose Lake porphyry (unit AMLp). These relationships indicate that the alteration and mineralization there occurred after the emplacement of the porphyry. This timing is significant because the alteration and mineralization at the barren sulfide zone is similar, and is generally believed to be related, to the main alteration and mineralization at Hemlo (e.g., Kuhns et al., 1994).

Ore Genesis

Genetic models previously proposed for the Hemlo gold deposit include epithermal and syngenetic models (e.g., Cameron and Hattori, 1985; Goldie, 1985; Valliant and Bradbrook, 1986), shear zone models (e.g., Burk et al., 1986; Hugon, 1986; Muir, 1997), porphyry models (Kuhns, 1988;

Kuhns et al., 1994; Johnston, 1996) and a late replacement skarn model (Pan and Fleet, 1995). These models are discussed below in the context of the results of this study.

To a large degree the debate over the genesis of the Hemlo gold deposit stemmed from a lack of understanding of the stratigraphy and the uncertainty concerning the protoliths of the lithologic units that are spatially closely associated with the ore. Although the alteration mineral assemblages (K-feldspathic and sericitic alteration) and metal abundances (enrichment in Au, Mo, As, Sb, Hg, and Tl) indicate that the mineralization fluids had a magmatic source (e.g., Burk, 1987; Kuhns, 1988), whether the deposit is a classical porphyry deposit associated with the Moose Lake porphyry, as suggested by Johnston (1996), has been subject to debate. Whether the Moose Lake porphyry is an intrusive body as envisaged by Johnston is critical to this debate. The present study, as well as most previous work (e.g., Muir 1982b, 1997; Burk et al., 1986; Valliant and Bradbrook, 1986), shows that the porphyry is volcanic in origin. No evidence is found that it is an intrusive complex that contains multiple intrusive phases as suggested by Johnston (1996). Other observations or interpretations that are inconsistent with the classical porphyry model include (1) the zones of alteration and mineralization are located at the stratigraphically lower, not the upper, contact of the Moose Lake porphyry; (2) the main protolith of the ore is not the Moose Lake porphyry, and the contact between the two is in general very sharp, and (3) the relationship at the barren sulfide zone indicates that the alteration and mineralization occurred significantly later than the emplacement of the Moose Lake porphyry and, therefore, the mineralization fluids could not have been directly related to the porphyry or to any deeper level intrusion comagmatic with the porphyry. Dating of zircons from the mineralized aplite dike described above indicates that mineralization is possibly >10 m.y. younger than the Moose Lake porphyry (Davis, 1998).

The uncertainty concerning the relative timing of alteration and mineralization has also contributed to the debate over the genesis of the Hemlo deposit. This study shows that the main alteration and mineralization occurred before G_2 or early during G_2 deformation, but definitely prior to G_3 deformation and before peak metamorphism. This means that it could not have been related to dextral transcurrent shearing (e.g., Hugon, 1986) that characterizes G_3 deformation, and that it could not have taken place during post-G_3 late calc-silicate alteration (e.g., Pan and Fleet, 1995). As mentioned above, the dominant alteration associated with the main mineralization at Hemlo is feldspathic and sericitic (now muscovitic owing to metamorphism) alteration, not calc-silicate alteration. Au mineralization after G_2 deformation is not pervasive and is best explained as a result of remobilization.

A syngenetic origin for the deposit is also considered to be unlikely on the basis of the results of this and previous studies. As discussed above, there is evidence that alteration and mineralization took place significantly after the emplacement and deposition of the enclosing and hosting rocks (e.g., the Moose Lake porphyry). In addition, a syngenetic model cannot readily explain the evidence for syn-G_2 mineralization and the spatial association of the deposit with the Hemlo shear zone. It also appears inconsistent with the conclusion of Thode et al. (1991) that the sulfur sources for barite and pyrite at Hemlo are separated in space and time. It should also be noted that the faults that Valliant and Bradbrook (1986) invoked as synvolcanic fluid conduits in their syngenetic model are brittle structures that postdated both G_2 and G_3 deformation. They are too young to be relevant.

Other constraints on the genesis of the deposit that result from this study include the following: (1) a mafic fragmental unit and a barite horizon, occurring at the stratigraphic lower contact of the Moose Lake porphyry, are spatially closely associated with the ore zones, (2) the mafic fragmental unit is most likely an altered felsic fragmental rock, and (3) the protolith of the ore is mainly the fragmental unit and the barite, but also includes the calc-silicate-band–rich wacke (hanging-wall and footwall sediments) and locally the fragmental portion of the Moose Lake porphyry. The above observations and interpretations indicate that the location of alteration and mineralization was probably controlled by the stratigraphically lower contact of the Moose Lake porphyry and by the fragmental rock and barite at the contact. In addition, the deposit is spatially associated with the Hemlo shear zone and occurs dominantly in the east-southeast-trending segment of the shear zone.

Two possible scenarios that are most consistent with the data are schematically shown in Fig. 30A, B. In scenario A (Fig. 30A), mineralization occurs as a stratabound replacement before folding; in scenario B (Fig. 30B), as a stratabound replacement early during folding. If all the timing relationships interpreted above are correct, then scenario B is more likely than scenario A. In both scenarios, the contact between the Moose Lake porphyry (unit AMLp) and the hanging-wall and footwall sediments (unit Acw) and the (permeable) fragmental unit (Amf) at the contact are considered as mechanical traps, and the barite horizon at the contact as a chemical trap (see also Burk, 1987; Thode et al., 1991). It is suggested that when upward-moving Au-Mo–bearing magmatic fluids arrived at the porphyry (AMLp)-sediment (Acw) contact, they were trapped under the massive porphyry and moved along the permeable fragmental unit (Amf). In the process, the fluids were oxidized by reacting with the barite along the horizon, as suggested by Thode et al. (1991) on the basis of sulfur-isotope geochemistry, and Au-Mo was deposited at the main and lower ore zones. In scenario B, the barite, as an incompetent layer, may also have helped to localize mineralization by localizing deformation and thus increasing permeability along the horizon (see also Burk, 1987). Mineralization also occurred in zones parallel to the axial surface near the hinge of the Moose Lake fold in scenario B.

In the barren sulfide zone, alteration and mineralization occur at the stratigraphically upper contact of the Moose Lake porphyry or at the contact between the porphyry and the cummingtonite schist (unit Acs), probably because the porphyry there is mainly fragmental. It was thus permeable and could not trap the mineralization fluids. The fluids passed through the porphyry, and altered and mineralized the porphyry and the overlying sediments (protolith of the cummingtonite schist) at the contact instead.

Scenario A can readily explain the stratigraphic setting of the deposit, and it is consistent with the interpretation that the fragmental unit was permeable during mineralization and served as a mechanical trap. However, like the syngenetic

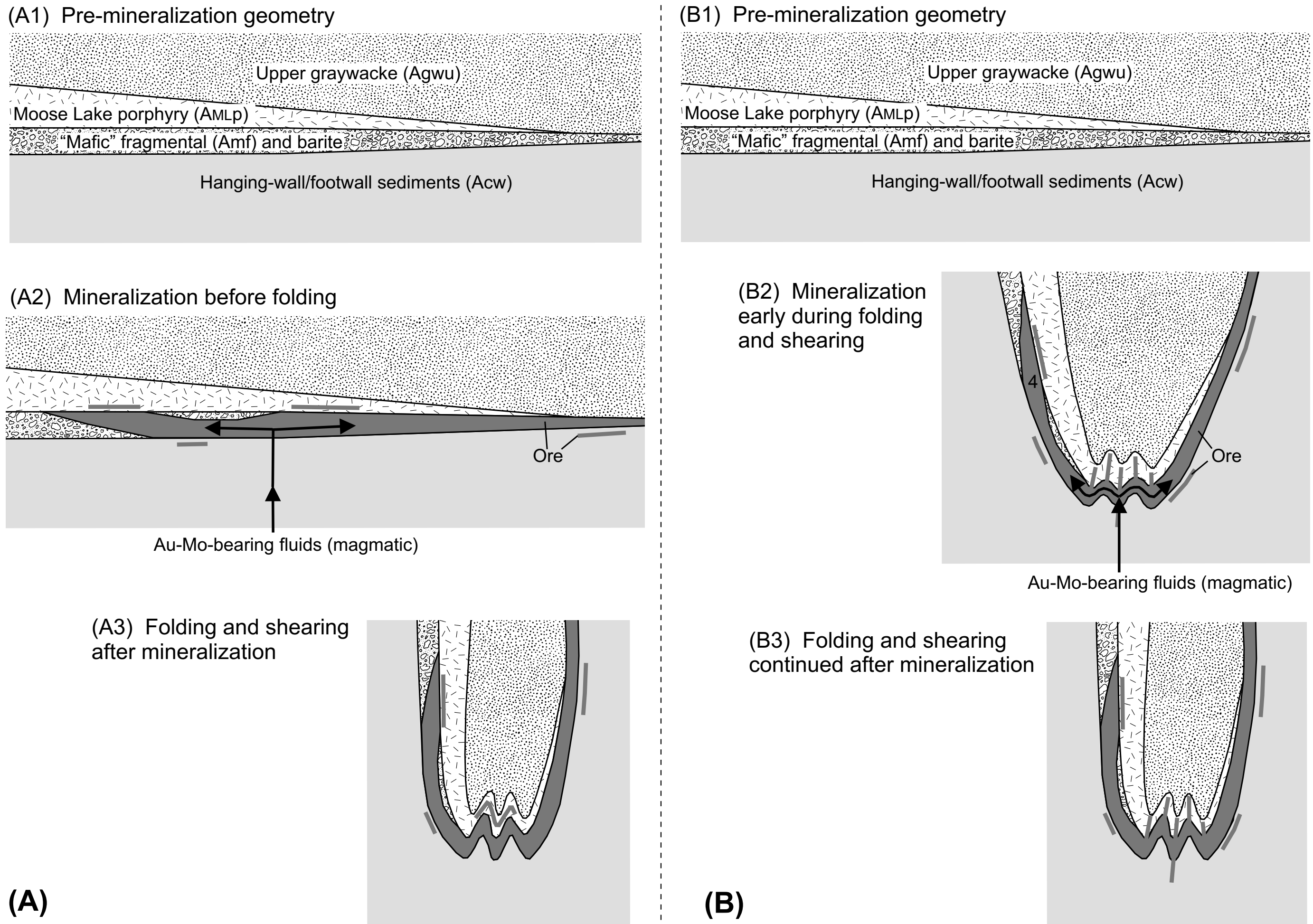

FIG. 30. Schematic diagrams showing two possible scenarios for the geologic evolution of the Hemlo camp. A. Mineralization before folding and shearing. B. Mineralization early during folding and shearing. The deformation shown occurred in the Hemlo shear zone that is interpreted to have served as a conduit for Au-Mo–bearing fluids in scenario B. See text for discussion.

model, it cannot readily explain the close spatial association between the deposit and the Hemlo shear zone, especially the apparent control of the location of alteration and mineralization by the geometry of the shear zone. It also requires that the potassic alteration and mineralization that occurred during G_2 deformation were related to remobilization. However, there is no evidence for a remobilization event that involves potassic alteration (Williams-Jones et al., 1998).

Scenario B can readily explain the spatial association of the deposit with the Hemlo shear zone and the evidence for syn-G_2 mineralization. In this scenario, the east-southeast–trending segment of the shear zone may have served as a conduit for Au-Mo–bearing fluids. Considering that the shear zone is interpreted as a sinistral transpressional zone, this segment is probably a restraining bend, and restraining bends in shear zones are effective structural traps for mineralization (Sibson et al., 1988; Etheridge, 1991; Sibson, 1991), although they may not be as effective as releasing bends. At restraining bends rocks are more deformed and thus have increased permeability. In this scenario, the alteration and mineralization may have started at the very early stage of deformation when the fragmental rock was still permeable enough to serve as a mechanical trap. The alteration and mineralization may have continued when the rocks were (brittle-)ductile and mineralization in zones parallel to the axial surfaces of F_2 folds took place. In this scenario, the stratigraphic setting of the deposit can also be explained by the presence of barite, which may have served as both a chemical and mechanical trap, as discussed above. In evaluating the validity of this scenario, one should keep in mind that G_1 and G_2 deformation may be related to a single episode of progressive deformation, and there may not be any folding or ductile shearing before the main alteration and mineralization event shown as stage B2 in Fig. 30B.

Both scenarios A and B can readily explain the deformation of the orebody by G_2 and later deformation. To test whether scenario B is more likely than scenario A, additional work is needed. For example, it is important to reexamine whether the evidence documented above for syn-G_2 mineralization is indeed related to the main mineralization or a result of remobilization. A demonstration that it resulted from remobilization would lend support to scenario A. Confirmation that it was related to the main mineralization would further support scenario B. A third possibility is a combination of scenarios A and B in which the main mineralization started before folding and continued early during folding.

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