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PETROGENESIS OF THE LICK FORK Ni-Co PROSPECT,
FLOYD CO., VIRGINIA

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Walter Wrightson, Jr.

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3063004

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THIS THESIS IS DEDICATED

TO LAURA

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Finally, a special thanks goes to my wife and best friend, Laura, who keeps my life in balance and harmony.

ABSTRACT

This thesis concerns the petrogenesis of the Ni-Co sulfide mineralization of the Lick Fork body in N.E. Floyd Co., Virginia. The host rock consists of steeply dipping layered ultramafic and mafic units of hornblende-peridotite, gabbro and hornblende-gabbro, in a high-grade metamorphic terrain (granulite facies). Sulfides comprised of pyrrhotite, marcasite, pentlandite, violarite, chalcopyrite, and pyrite form a "net" textured ore, confined to the ultramafic hanging wall unit.

The primary silicates have equilibrated to granulite facies metamorphism as indicated by the average $K_{d(mg-Fe^{2+})}^{Opx-Cpx} = 0.57$, $MgO + FeO + Fe_2O_3$, vs. Al_2O_3 in orthopyroxenes; and Ti contents, Al^{iv}/Al^{vi} ratios and alkali contents of amphiboles.

Mg/Mg+Fe variation for pyroxenes, hornblende and biotite is reverse from that expected from typical in situ magmatic differentiation, but systematic variation of Mg/Mg+Fe with increasing modal percent mafic minerals suggest an origin by magmatic differentiation rather than metamorphic differentiation.

Prograde reaction textures are rare; however, the comparison of Mg/Fe ratios of coexisting hornblende and pyroxenes, Cpx/Opx ratios and plagioclase compositions are similar to those derived from the theoretical breakdown reactions of hornblende, indicating the anhydrous phases are derived from the prograde dehydration of hornblende. Retrograde reactions of $Cpx \rightarrow Hb$, brought about by the volatiles released

during dehydration of primary hornblende, occurred at peak metamorphism. The primary silicates were then deformed by tectonic processes which included faulting localized at the hanging wall contact.

The absence of metamorphic sulfide textures, and the textural and chemical disequilibrium of coexisting sulfide-silicate phases argue for a post-metamorphic origin of the sulfides. Movement of hydrothermal fluids along fractures altered the primary silicate phases and was the source of sulfide emplacement as evidenced by replacement textures of silicates by sulfides. Sulfides replaced favorable foliated anhydrous phases resulting in the observed foliated "net" textures. Secondary sulfide mineralization was formed by supergene processes.

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CHAPTER I

INTRODUCTION

There is, presently, considerable debate over the origin of Ni sulfide deposits of mafic and ultramafic association: whether or not the sulfides are truly magmatic in origin, evolving from an immiscible sulfide-oxide melt (Naldrett, 1980), or they are hydrothermal in origin, whereby sulfides have replaced the original silicates (Fleet, 1980).

The Lick Fork deposit, a nickel-cobalt sulfide occurrence of pyrrhotite, pentlandite, and chalcopyrite, is hosted by a small but complex mafic intrusion in a high grade metamorphic terrain (granulite facies). The deposit is located in the northeastern corner of Floyd County, Virginia ($37^{\circ}05'$ N.; $80^{\circ}12' 20''$ W.) at the confluence of Goose Creek and Flat Run.

Interpretation of sulfide mineralization in the deposit is controversial. The Lick Fork sulfides are interpreted by Ross (1935) as being hypogene but secondary in origin. A magmatic origin of the sulfides from an immiscible sulfide melt is proposed by Craig and Higgins (1975), although they did not establish any evidence for their hypothesis.

The purpose of the present investigation is to determine the genesis of the sulfide mineralization in the Lick Fork occurrence. However, the lack of adequate petrologic data on the body requires a detailed petrologic investigation of the host rocks.

Thus, the two main aspects of the present research are as follows:

1. A petrogenetic model for the evolution of the host rocks, based on the observable field relationships, and petrographic and chemical variations within the host rocks; and
2. The origin of the sulfides within the framework of the host rock petrogenesis, based on distribution, textures and compositions of the sulfides.

CHAPTER II

REGIONAL GEOLOGY

Country Rock Lithologies

The lithologies of Floyd County, Virginia, were mapped originally by Dietrich (1959) and are depicted in Figure 1. They are Cambrian to Upper Precambrian (Proterozoic) in age. The Paleozoic rocks consist of the Unicoi, Hampton, and Rome Formations. The Precambrian rocks are of two relative ages (Dietrich, 1959). The younger rocks occur in central and southern Floyd County, and comprise the Lynchburg Gneiss, the Willis Phyllite, the Alum Phyllite, and the associated amphibolites and amphibole-rich rocks. The older Precambrian basement rocks, which comprise the northern third of Floyd County, are the Marshall, Lovingsston and Pedlar Formations of the Virginia Blue Ridge Complex. These lithologies are summarized in Table 1.

The Lynchburg Gneiss varies from a mica schist to a mica gneiss, consisting primarily of muscovite, biotite and quartz. It contains porphyroblasts of garnet, kyanite, staurolite, and numerous amphibole masses. The Willis Phyllite is gradational into the Lynchburg Gneiss, although no bottom unit of the Willis Phyllite has been found in Floyd County. It is a highly crenulated phyllite, steel gray in color, and contains weathered garnets. Dietrich (1959) interpreted the Willis Phyllite to be a metamorphosed siltstone. The Alum Phyllite is a highly weathered fine-grained phyllite which appears to lie conformably within the Lynchburg Gneiss; it probably represents a metamorphosed

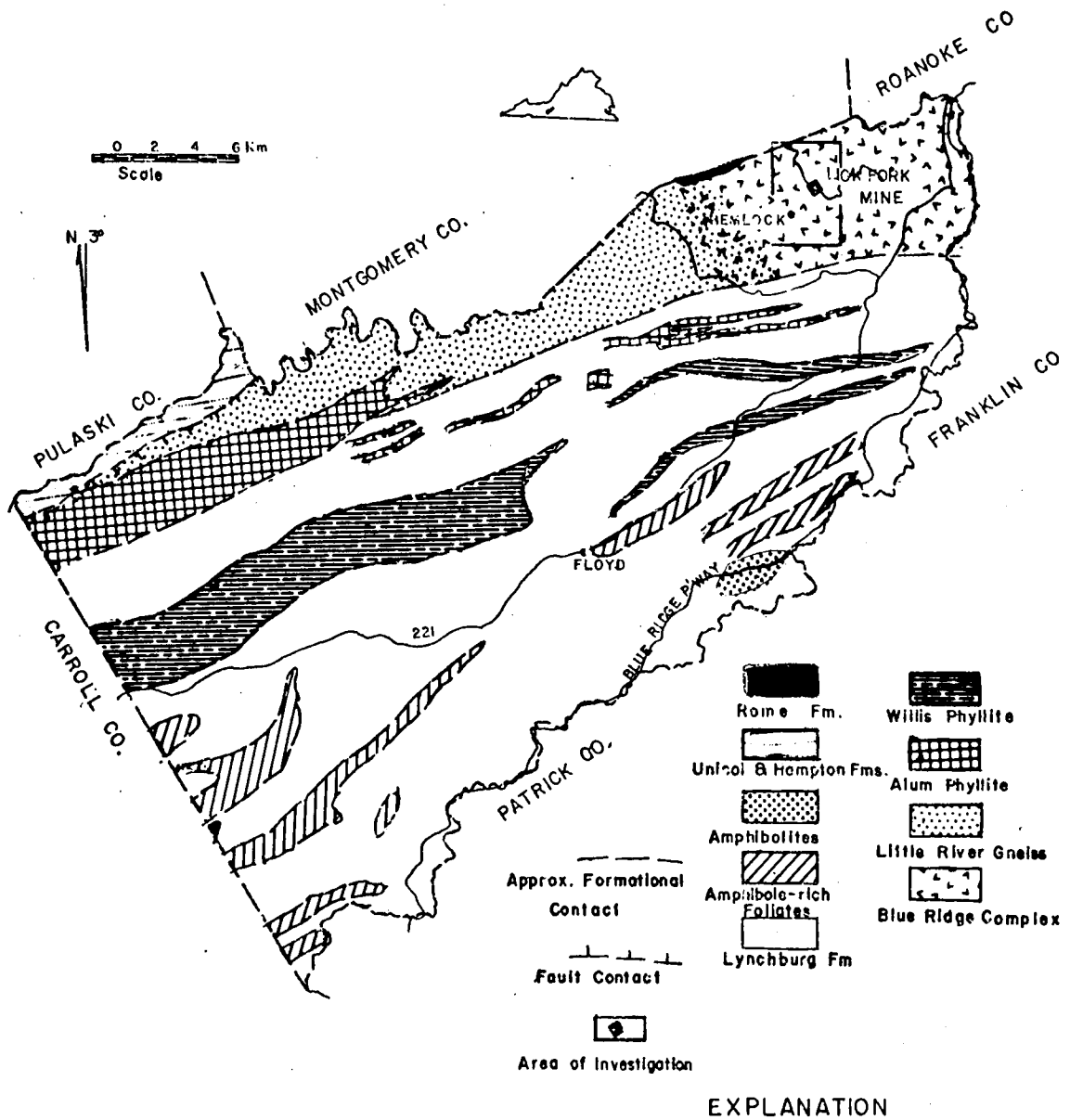


Figure 1. Geology of Floyd Co., Virginia (from Dietrich, 1959).

TABLE 1
REGIONAL GEOLOGY OF FLOYD CO., VIRGINIA

Formation	Description
<u>Paleozoic</u>	
Unicoi Hampton Rome	Unmetamorphosed clastic sediments
<u>Precambrian</u>	
Amphibolites and Amphibole-rich rocks	Concordant with surrounding Lynchburg Fm. Reworked pyroclastic flows and sills.
Lynchburg Gneiss	Mica schist and gneiss, mainly muscovite, biotite, and quartz pebbles. Contains garnet porphyroblasts, kyanite and staurolite, also numerous amphibole masses.
Willis Phyllite	Grades into Lynchburg Fm., has relict bedding. Metamorphosed siltstone.
Alum Phyllite	Fine-grained phyllite, highly weathered exposures. Metamorphosed siltstone or shale.
Little River Gneiss	Highly sheared gneiss with blue quartz "eyes" and feldspar augen.
Virginia Blue Ridge Complex	
Marshall Fm.	Micaceous granitic gneiss
Lovington Fm.	Quartz feldspar augen gneiss. Little River Gneiss equivalent (?).
Pedlar Fm.	Pyroxene-syenite (Pyroxene granodiorite). Charnockite.

From Dietrich, 1959.

siltstone or shale (Dietrich, 1959). The amphibolites and amphibole-rich rocks are well foliated, and occur as concordant tabular masses within the Lynchburg Formation. They consist almost wholly of fine-grained amphibole needles, but may contain small quartz lenses and, occasionally, some clinozoisite laths. According to Dietrich (1959), the amphibolites are reworked pyroclastic flows and sills.

The older Precambrian rocks are bounded on the northwest by Fries Fault, which is a thrust fault overlying the Paleozoic sediments. Dietrich (1959) defined two formations within the earlier Precambrian. These are the "undifferentiated Blue Ridge Complex" forming the crystalline basement rocks of southwest Virginia, and the Little River Gneiss. The Little River Gneiss is interpreted as being metasedimentary in origin, and possibly equivalent to the Lovington Gneiss, which is considered to be an orthogneiss by Bloomer (1950). Dietrich (1959) described the "undifferentiated Blue Ridge Complex" as consisting of "hypersthene granodiorites" and granitic gneisses which are undifferentiable in the field. The "undifferentiated Blue Ridge Complex" is more properly called the "Virginia Blue Ridge Complex" by other workers (Milici et al., 1963). It is separable into five mappable units (Brown, 1958). Three of these units were found by this worker in the Virginia Blue Ridge Complex in Floyd County. These are: the Lovington Formation, a quartz feldspar augen gneiss; the Marshall Formation, a micaceous granitic gneiss; and the Pedlar Formation, a pyroxene syenite (Figure 2). The Marshall and Lovington Formations are probably equivalent to Dietrich's (1959) undifferentiated granitic gneisses, and the Pedlar to the "hypersthene granodiorites" (Table 1).

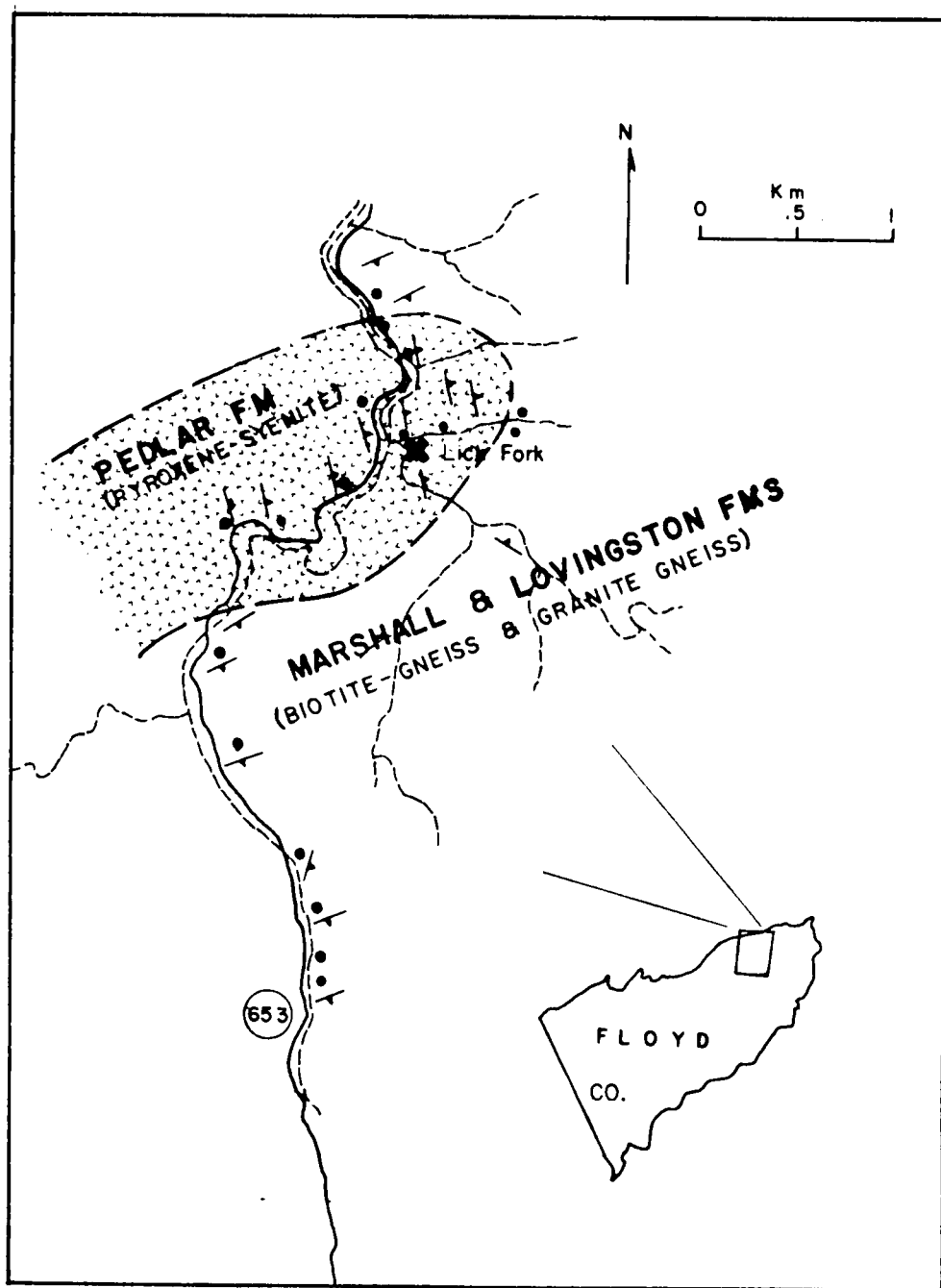


Figure 2. Rock types in the vicinity of the Lick Fork ultramafic-mafic body, Floyd Co., Virginia. The solid circles represent locations of samples from the country rocks collected for this study.

The Lovington Formation is a quartz-feldspar-biotite gneiss, varying in fabric from a feldspar-biotite gneiss to a quartz-augen gneiss. The feldspar-biotite gneiss consists of an assemblage of fine to medium porphyroblasts of perthitic feldspar with abundant epidote in a finer-grained matrix of ragged cataclastic quartz and highly foliated layers of biotite giving the rock a gneissic texture. Rounded zircon grains and hypidioblastic garnet occur intergranular to the biotite. Scattered grains of leucoxene with relict cores of ilmenite occur as small porphyroblasts. The quartz-augen biotite gneiss is similar in mineralogy to the feldspar-biotite gneiss, and is distinguished by coarse quartz "eyes" and perthitic feldspar in a finer-grained micaceous quartz matrix. The coarser quartz augen actually consist of smaller recrystallized quartz grains. Biotite, muscovite, and ragged lenticular quartz comprise the banded matrix surrounding the porphyroblasts. Zircon and epidote are present in small amounts, but unlike the feldspar-biotite gneiss, garnet is not observed in thin sections of the augen gneiss.

The Marshall is a pink to light gray, fine- to medium-grained micaceous granitic gneiss with hypidioblastic orthoclase porphyroblasts in a fine-grained quartz-muscovite matrix. The mineralogy is similar to the quartz-feldspar augen gneiss described above, but biotite and muscovite are less abundant which accounts for the more granitic appearance of the Marshall Formation. Scattered epidote and traces of leucoxene also occur. The feldspar is often sericitized.

The Pedlar Formation is a hypersthene-bearing rock of felsic composition. Generally, it is a gray-greenish rock with a waxy luster in fresher samples. In more weathered occurrences, the Pedlar is light gray to medium white with grayish streaks of pyroxene bands. Textures are granoblastic amoeboid with hypidioblastic quartz, perthitic orthoclase, albite-rich plagioclase, orthopyroxene and accessory biotite and zircon. Feldspar is partially sericitized, and pyroxenes are commonly relict grains partially altered to amphibole and epidote. Amoeboid garnet is often associated with magnetite. Textures and mineralogy of the Pedlar Formation in this area suggest that it is a charnockite, and may be properly be classified as a pyroxene alkali syenite using Tobi's (1971) classification of charnockites.

The formation names and lithologies described above are in good agreement with descriptions of other workers in Greene and Madison Counties, Virginia (Allen, 1963), Abermarle County, Virginia (Nelson, 1962) and in the counties of the Lynchburg Quadrangle (Brown, 1958).

Structure

The basement rocks of the Virginia Blue Ridge Complex extend as a belt 240 km long and 10 km in maximum width along the southeastern Blue Ridge and northwestern Piedmont provinces (Dietrich, 1959). The older Precambrian rocks of the Virginia Blue Ridge Complex are bounded on the northwest by Fries Falut, which marks the overthrusting of the Blue Ridge Complex on the Paleozoic rocks of the Hampton, Unicoi, and

Rome Formations, and is overlain toward the southeast by younger schists and gneisses of the Lynchburg Formation.

Structures within the Blue Ridge Complex are complicated. The Marshall gneiss and the Lovington gneiss are intergradational, and mapping a single rock type within these units is difficult. Such intergradational features has been described by Bloomer (1950) for the Blue Ridge Complex in central Virginia.

The pyroxene syenite of the Pedlar Formation occurs as a smaller body (about 1.5km^2) within the intergradational Marshall and Lovington Formations. The charnockite body comprises a structural high known as the "Hemlock High." No sharp contacts have been observed at the margins of the pyroxene syenite; however, the charnockite changes character from a banded rock to a more highly foliated gneiss and becomes interlayered with the surrounding gneisses of the Marshall and Lovington Formations.

Foliation in the charnockite is $N 10^\circ E, 65^\circ N$, whereas in enclosing Marshall and Lovington gneiss it is $N 50^\circ E, 65^\circ S$. The significance of this anomaly is not known at this time, but it may be related to the formation of the charnockite during intertectonic periods.

CHAPTER III

ROCKS OF THE LICK FORK BODY

The Lick Fork Body

The Lick Fork body occurs within the Pedlar Formation in the northeast corner of Floyd County at the confluence of Goose Creek and Flat Run. The body is exposed in adit facing the Lick Fork Creek, and consists of almost vertical layers of mafic and ultramafic lithologies which give the body a dike-like appearance. The geometry of the adit prohibits determination of actual thickness of the body since a footwall contact is not exposed, but Watson (1907) mentions a thickness of 18-22 ft (6-7m). Sulfide mineralization consisting of pyrrhotite, pentlandite, violarite, chalcopyrite and marcasite are confined predominantly to the ultramafic unit of the Lick Fork body.

Rock Types

The Lick Fork body consists of three rock types (See Appendix A-IV). These are: (1) hornblende-peridotite (the pyroxenite of Ross (1935), (2) gabbro and (3) hornblende-gabbro (the gabbro and mica gabbro of Ross (1935)).

1. Hornblende-peridotite. This is the sulfide ore bearing rock containing 45% hornblende, 24% orthopyroxene ($\text{En}_{78}, \text{Wo}_1$) (mineral abbreviations are listed in Table C-1 in the Appendix), 24% olivine (Fo_{74-76}), 7% augite ($\text{En}_{43-45}, \text{Wo}_{45-46}, \text{Fs}_{9-11}$) with accessory biotite and traces of zircon. Olivine is commonly altered to serpentine and

the orthopyroxenes are partially altered to mica ($\pm$ chlorite). Hornblende may be partially altered along fractures to tremolite and calcite, and augite is altered to hornblende. Opaque minerals comprise up to 30% of the rock. The sulfides consist mainly of pyrrhotite, marcasite, and chalcopyrite, with traces of pentlandite, violarite and pyrite. The oxides are green spinel (pleonaste) and magnetite-ilmenite intergrowths.

2. Gabbro. The major silicate minerals of the gabbro comprise 56% plagioclase (An_{57}), 31% orthopyroxene ($\text{En}_{60-62}, \text{Wo}_1$), 12% augite ($\text{En}_{40}, \text{Wo}_{45}, \text{Fs}_{15}$) and traces of biotite. Alteration is not as prominent in the gabbro as in the hornblende-gabbro, but orthopyroxenes are partially altered to uraltite along grain boundaries, and feldspars are partially sericitized. Opaque minerals are primarily ilmenite; however, some pyrrhotite occurs as fine disseminations in altered pyroxenes. Biotite is occasionally rimmed by magnetite, and rutile is oriented along crystallographic planes within the biotite. The gabbro is finer grained than both the hornblende-peridotite and the hornblende-gabbro.

3. Hornblende-gabbro. This rock consists of 3-5% hornblende, 2-6% biotite, 7-12% augite ($\text{En}_{43-45}, \text{Wo}_{45-46}, \text{Fs}_{10-11}$) 20% orthopyroxene ($\text{En}_{60-72}, \text{Wo}_1$) and 10-17% plagioclase (An_{40-43}). Feldspars are commonly altered to sericite and orthopyroxene to uraltite. Opaques occur in trace amounts intergranular to silicates, and rarely as rounded blebs within the primary silicate phases. The sulfides present are pyrrhotite, chalcopyrite, and pyrite. Oxides

include magnetite, ilmenite, and hematite. The andesite described by Ross (1935) was not observed by this worker. This may be due to the absence of the complete exposure of the Lick Fork body in the adit.

Structure

The Lick Fork body is exposed in an adit facing the Lick Fork Creek. Dimensions of the three sides of the adit are approximately 8m x 6.5m x 9m (Figures 3, 4). The strike of the body is parallel to foliation of the enclosing pyroxene syenite (N 10°W). The dip of the units (70°E) is transgressive to regional foliation. A weak, but distinct foliation is also imprinted on the Lick Fork rocks in the form of subparallel biotite. An indistinct mineralogical banding composed of alternating felsic- and mafic-rich bands of about 3cm occurs in the hornblende-gabbro. Both foliation and banding are parallel to strike and dip of regional foliation.

On the west face (Figure 4A, 5c) the Lick Fork body appears as a small apophyse of gabbro, hornblende-gabbro, and a thin seam of sulfide-rich gossan separated by gently folded layers of pyroxene-syenite. Within the apophyse are small veins of country rock which have been offset and folded. The gabbro in the apophyse is highly foliated (N 90°W, 60°N) near its contact with the country rock. Slickensides along the hanging-wall contact of the Lick Fork body and the pyroxene-syenite indicate the presence of faulting. This is supported by the fact that rocks at this contact are intensely sheared, as observed in thin sections.

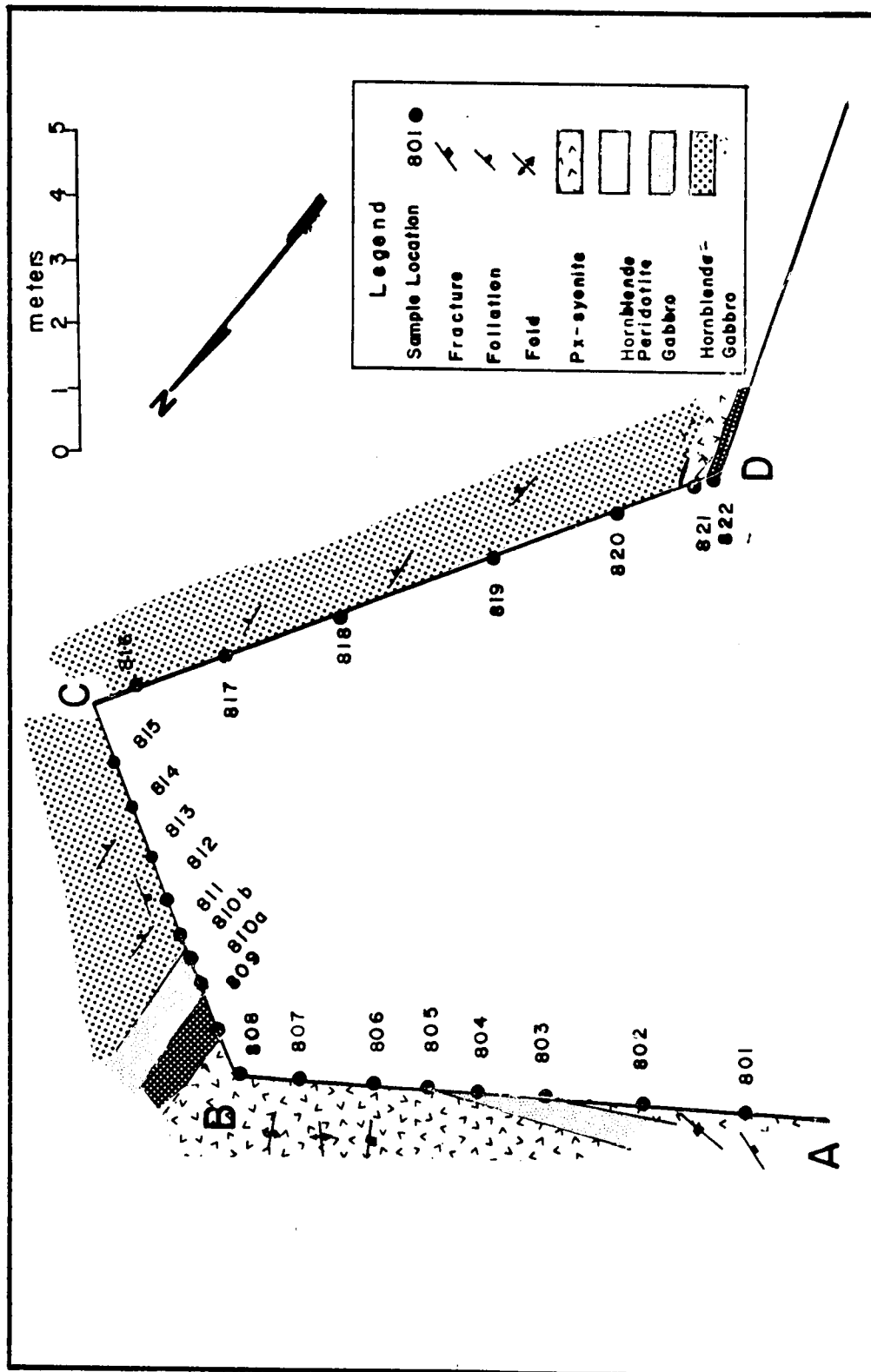


Figure 3. Plan view of the Lick Fork adit showing geology and sample locations.

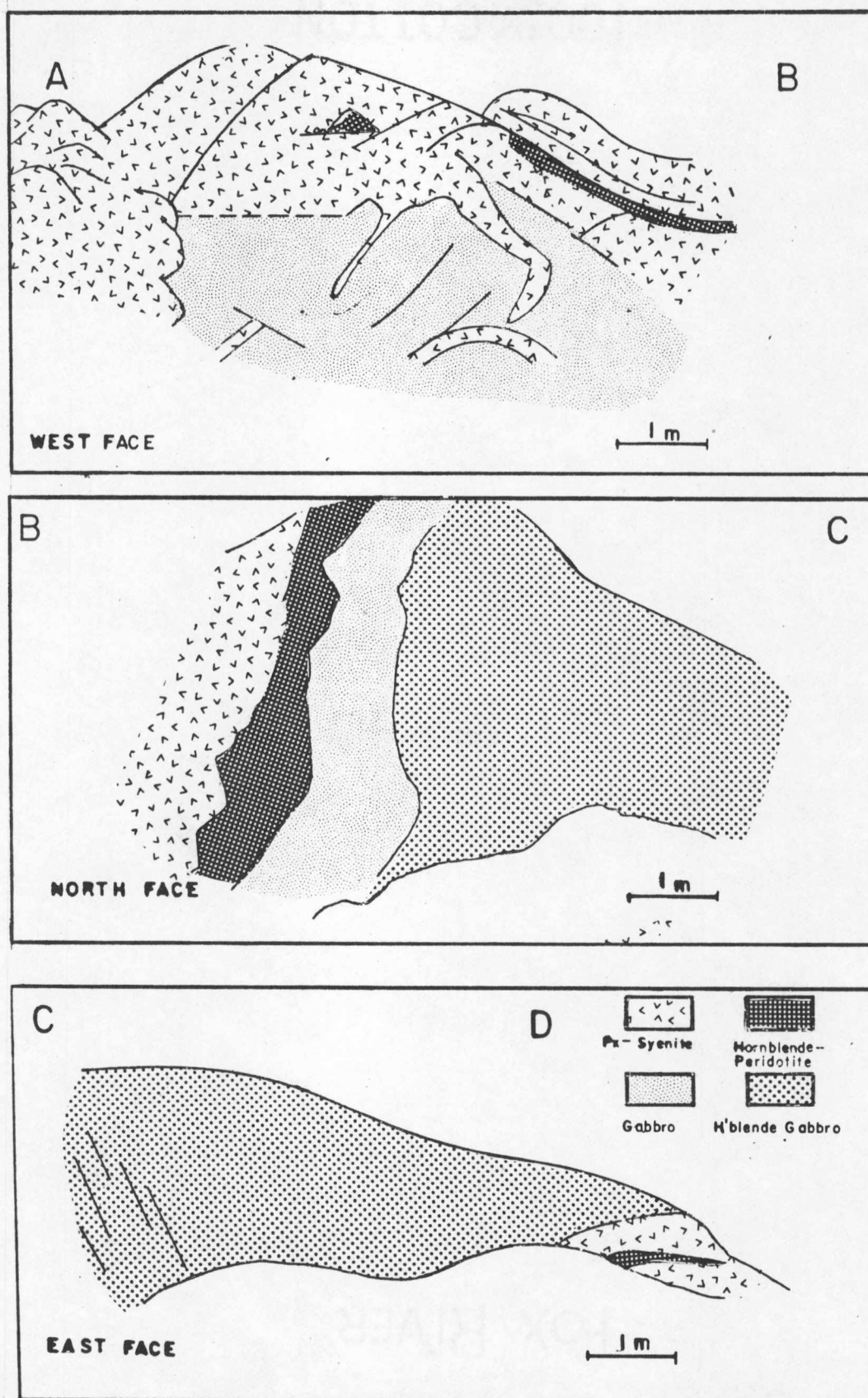
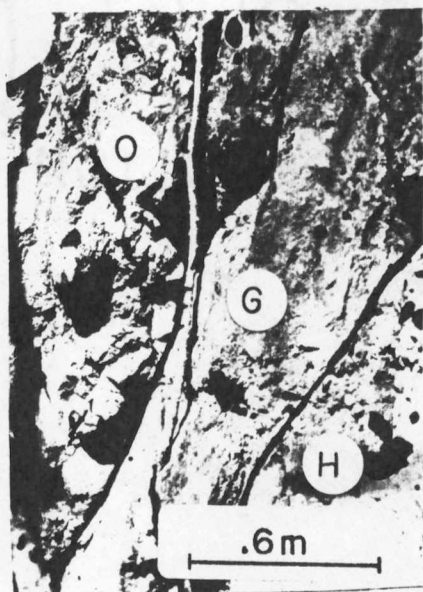


Figure 4. Schematic cross-sections of the Lick Fork adit. The lines of sections A-B, B-C, and C-D are shown in Figure 3.

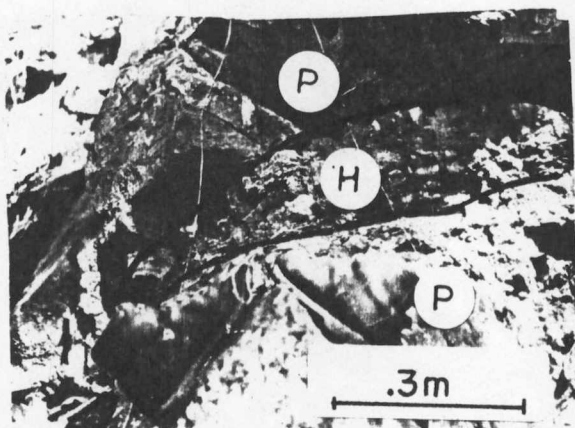
Figure 5. Field relationships of the rock types in the Lick Fork adit. Abbreviations:

O—Hornblendite
G—Gabbro
H—Hornblende-gabbro
P—Pyroxene-syenite

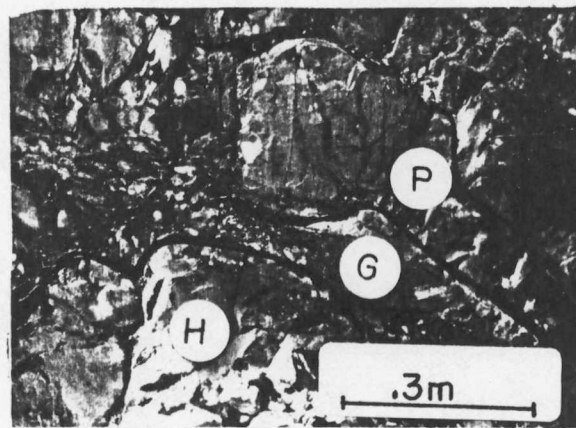
- a. Structural relationships of the North Face.
- b. Cross-cutting relationships of hornblendite to country rock (pyroxene-syenite) East Face.
- c. Cross-cutting relationships of gabbro to pyroxene-syenite country rock, West Face apophyse.



5a



5b



5c

Figure 5.

The North face (Figure 4b) is approximately normal to the strike of the Lick Fork body. It is along this face that the major lithological variation is most apparent. Stratigraphically, the body consists of a hanging wall unit of hornblende-peridotite (Figure 5a), about 1m in thickness, underlain by a 1.5m thick unit of gabbro, and a footwall of hornblende-gabbro of undetermined thickness. The geometry of the adit prevents the footwall contact of the hornblende-gabbro with the country rock from being exposed. The hornblende-peridotite, where it occurs in situ, is covered by a surficial gossan layer. Several relatively fresh samples were recovered from the mine dump for petrographic study.

The East face is primarily hornblende-gabbro with a small seam of sulfide-rich hornblende-peridotite at its southern exposure, which occurs in a transgressive relationship to the country rock (Figure 4c). This contact is on strike with the main hornblende-peridotite unit and is interpreted as a continuation of that unit.

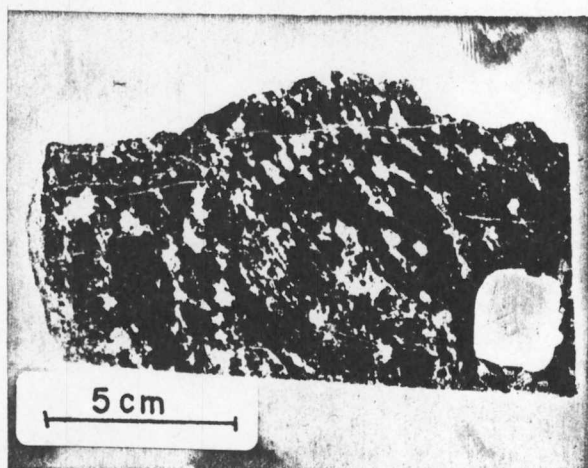
Silicate Petrology

Hornblende-peridotite. In hand specimen, the hornblende-peridotite is a medium-grained, melanocratic rock with disseminated sulfides exhibiting a weakly preferred orientation (Figure 6a).

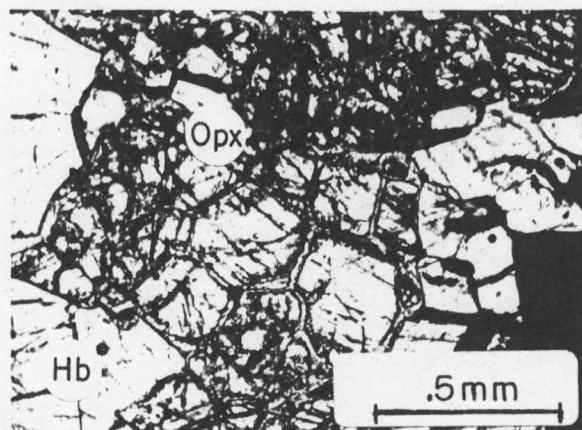
In thin section, the silicates are mostly medium-grained and granoblastic. Hornblende and orthopyroxenes commonly occur as polygonal aggregates with well defined dihedral angles and triple junctions (Figure 6b). Orthopyroxenes exhibit a faint pleochroism with a pink

Figure 6. Silicate petrology, the Lick Fork mafic-ultramafic body.

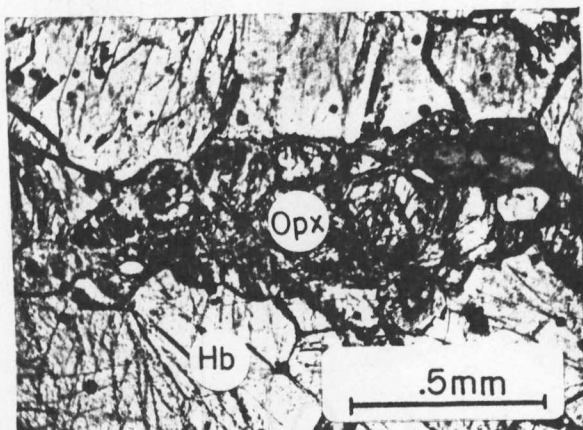
- a. Hand specimen of hornblende-peridotite showing disseminated sulfides. Specimen D-1.
- b. Hornblende-peridotite showing polygonal orthopyroxene in coarse-grained hornblende matrix. Pyroxenes are partially altered along grain boundaries. Specimen D-1, plane polarized light.
- c. Orthopyroxene "clots" in coarse hornblende matrix. Long axis of pyroxene clot is conformable to regional foliation in pyroxene-syenite. Specimen D-1, plane polarized light.
- d. Hornblende (gray) altering to orthopyroxene in hornblende-peridotite. Specimen D-1, plane polarized light.
- e. Clinopyroxene altering to hornblende in hornblende-peridotite. Specimen D-1, plane polarized light.
- f. Inclusions of green spinel (pleonaste) in augite of hornblende-peridotite. Specimen D-1, plane polarized light.



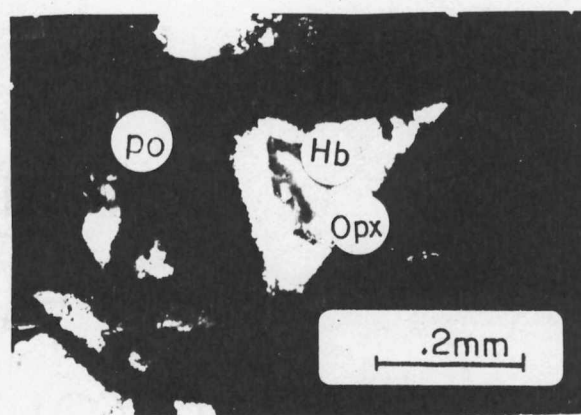
6a



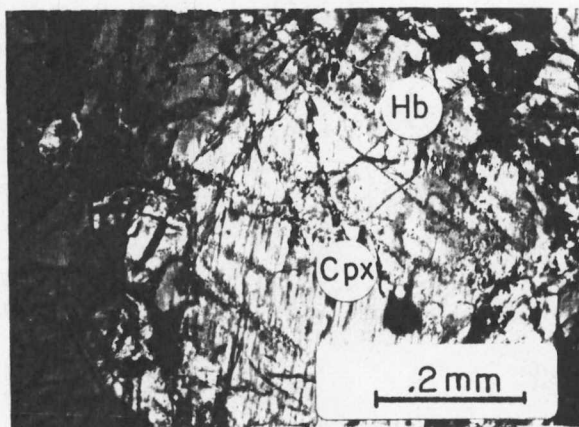
6b



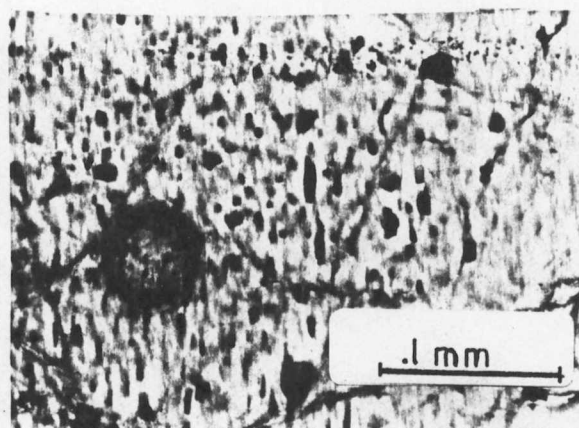
6c



6d



6e



6f

Figure 6.

tint, and generally occur as relict grains altered to chlorite and serpentine along grain boundaries. Aggregates or clots of finer-grained orthopyroxenes occur in a coarser matrix of polygonal hornblende. These clots commonly are elongated into short bands, the axes of which are parallel to other linear features within the rock (Figure 6c). Occasionally, the orthopyroxenes may occur as coarse amoeboid grains which exhibit twinning lamellae and undulose extinction. In one sample (Figure 6d), a corona of orthopyroxene is observed rimming an occluded hornblende grain; however, reaction textures of this type are scarce.

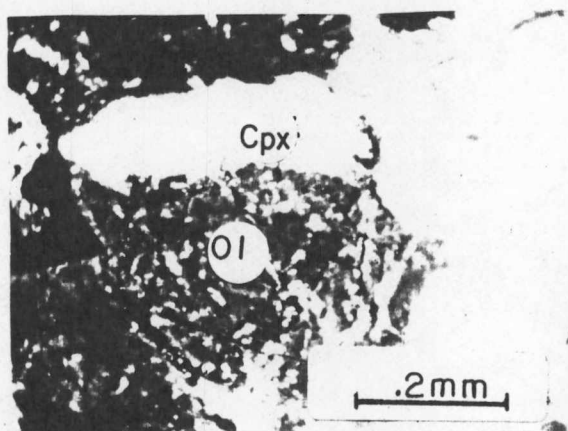
Augite is medium-grained and xenoblastic. Inclusions of green spinel (pleonaste) occur as small oriented platelets within the augite (Figure 6f).

Two textural varieties of hornblende occur. One is a coarse-grained polygonal variety ("primary" hornblende) which is green-brown in color, strongly pleochroic, and usually exhibits undulose extinction. It is generally coarser-grained than the orthopyroxenes. Although commonly a matrix material to the orthopyroxene clots, the hornblende may sometimes occur intergranular to the orthopyroxenes, or as occluded grains in a sulfide matrix. The second type of hornblende is a reaction product of augite ("secondary" hornblende) and may rim augite or occur along augite cleavage planes (Figure 6d).

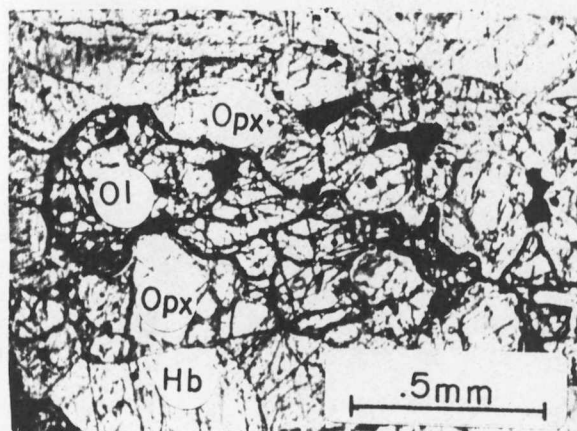
Unlike the orthopyroxenes which are generally polygonal, olivine is usually amoeboid, and is often embayed by pyroxenes and hornblende (Figure 7a). Occasionally, olivine is intergranular to the hornblende

Figure 7. Silicate petrology, the Lick Fork mafic-ultramafic body (hornblende-peridotite, gabbro).

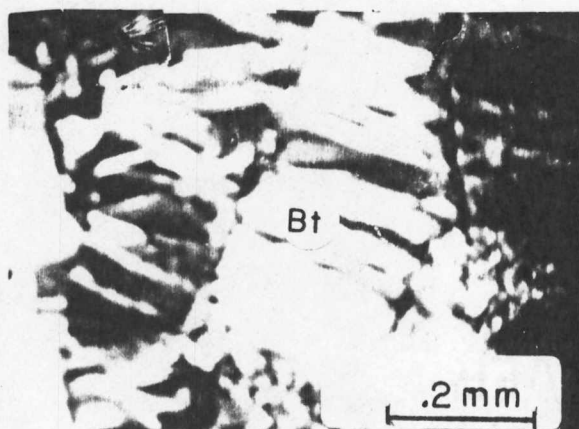
- a. Embayment texture of amoeboid olivine (dark gray) and augite (light) in hornblende-peridotite. Specimen D-1, crossed nicols.
- b. Amoeboid olivine intergranular to orthopyroxenes and hornblende in hornblende peridotite. Elongation of olivine is parallel to banding in hornblende-peridotite. Specimen D-1, plane polarized light.
- c. Deformed biotite in hornblende-peridotite. Specimen 809, crossed nicols.
- d. Orthopyroxenes altering to serpentine, chlorite and mica along grain boundaries in hornblende-peridotite. Note intergranular opaques. Specimen 809, plane polarized light.
- e. Hand specimen of gabbro showing distribution of mafic and felsic phases. Specimen 810A.
- f. Polygonal granoblastic texture of gabbro. Specimen 810A, plane polarized light.



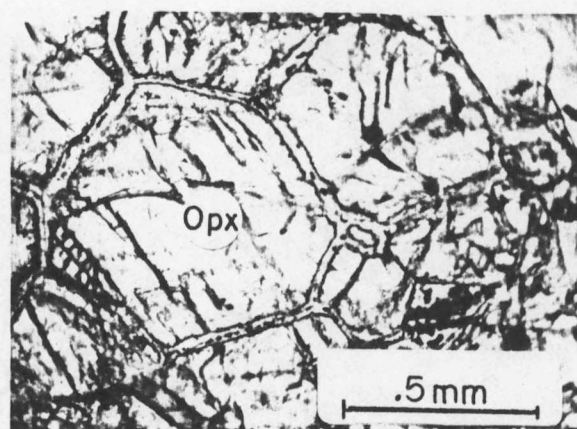
7a



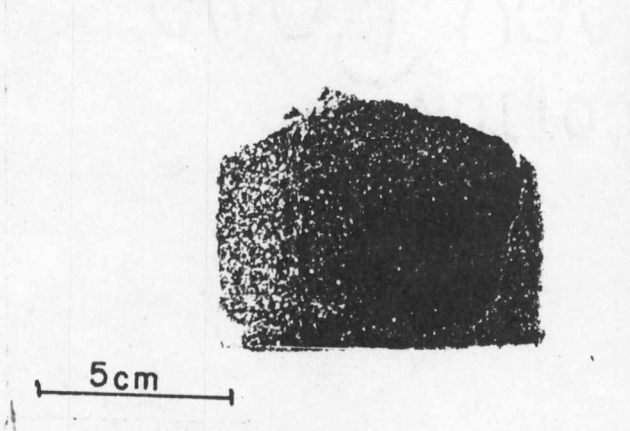
7b



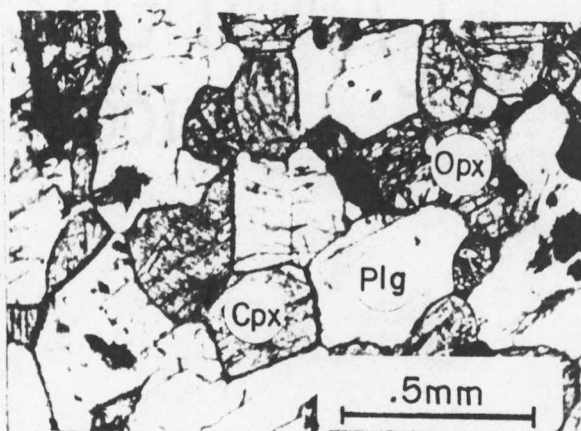
7c



7d



7e



7f

Figure 7.

and the pyroxenes (Figure 7b), and it often occurs within the pyroxene clots as elongated grains parallel to foliation.

Biotite is the most abundant accessory mineral in the hornblende-peridotite, and it appears to increase in abundance in the more highly altered samples. It is reddish-brown in color, and in thin sections shows ample evidence of deformation in the form of severely strained and deformed biotite laths (Figure 7c). Within the biotite are minute inclusions of a phase tentatively identified as rutile, which occur in the form of small "asterisks" (Deer, Howie, and Zussman, 1966).

The polygonal-granoblastic texture of the hornblende-peridotite is suggestive of a high-grade metamorphic environment. The amoeboid embayment textures and the intergranular nature of the olivine may have some bearing on the primary origin of this lithology. The significance of this feature will be discussed in a later section. Alteration of the ultramafic assemblages is indicated by uralitization and serpentinization of pyroxene and olivine, and by the alteration of hornblende to actinolite and calcite. In addition, many samples in the hornblende-peridotite zone are altered to clay minerals of undetermined composition. In the samples which are highly altered, relict orthopyroxene cores are rimmed by sericite and serpentine in which polygonal outlines of the original pyroxene are preserved by intergranular opaque minerals (Figure 7d).

Gabbro. The gabbro is a medium to dark gray fine-grained rock. In hand specimens (Figure 7e) mafic and felsic phases often occur as

distinct bands. In the west wall apophyse, the banding is transgressive to regional foliation.

The silicate minerals consist of nearly equal amounts of augite and plagioclase with accessory biotite. Textures are granoblastic, polygonal-equigranular (Figure 7f). Plagioclase is both untwinned and twinned. The twinning lamellae are generally spindle-shaped (Figure 8a) indicating deformation (Deer, Howie and Zussman, 1966). The plagioclase is also clouded with a fine rod-like phase. X-ray diffraction and energy dispersive methods were employed to determine the nature of this phase, but no positive identification could be made. This clouded texture has been interpreted by some workers as being indicative of progressive metamorphism of feldspar phases (Spry, 1969). Also, associated with the clouded plagioclases are minute inclusions of opaques. Plagioclase is highly altered to sericite along grain boundaries.

Orthopyroxenes are intergranular, commonly altering to uralite; however, the alteration is not as intense as in the hornblende-peridotite.

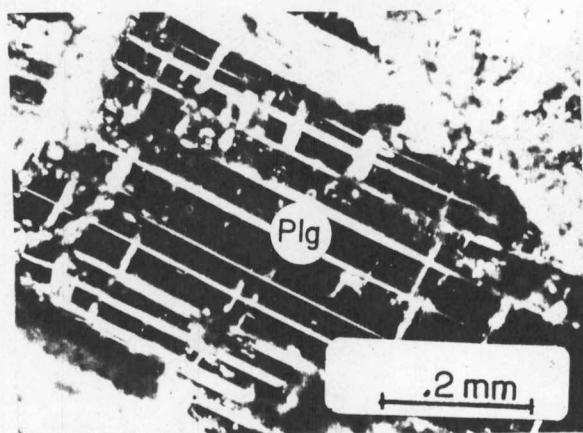
Unlike the amoeboid augite of the hornblende-peridotite, the augite of the gabbro is polygonal in shape. Also, augite of the gabbro shows no reaction textures to hornblende.

Biotite, which is reddish-brown, occurs in trace amounts in the gabbro and contains inclusions of rutile. Deformation textures are absent in the biotite of the gabbro.

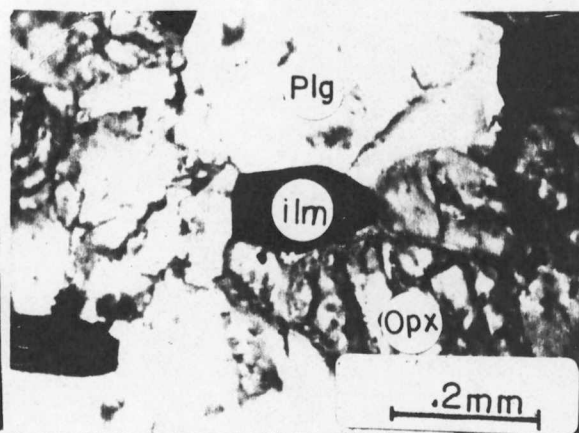
The dominant opaque phase in the gabbro is ilmenite which occurs as discrete grains intergranular to silicates (Figure 8b). Very fine oriented blebs of hematite are observable within the ilmenite. Traces of

Figure 8. Silicate petrology, of the Lick Fork mafic-ultramafic body (gabbro, hornblende-gabbro).

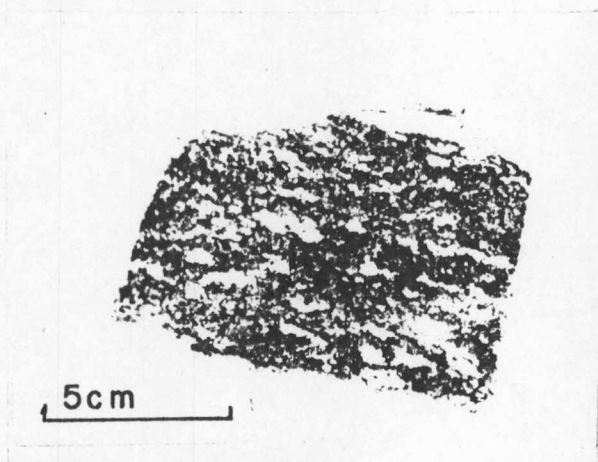
- a. Deformation twinning lamellae in plagioclase of gabbro. Note spindle-shaped albite twins. Specimen 810, crossed nicols.
- b. Ilmenite (dark) in gabbro. Note polygonal grain shape. Specimen 810, crossed nicols.
- c. Hand specimen of hornblende-gabbro, showing foliation due to alternation of mafic and felsic bands. Specimen 812, plane polarized light.
- d. Polygonal granoblastic texture in hornblende-gabbro. Specimen 813, crossed nicols.



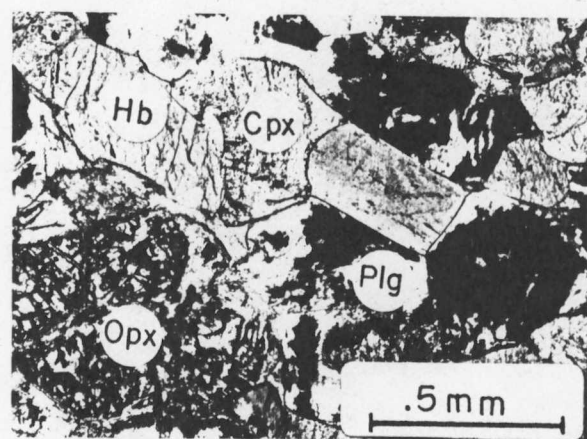
8a



8b



8c



8d

Figure 8.

pyrrhotite associated with alteration products of the mafic silicates occur as fine disseminations.

Hornblende-gabbro. The hornblende-gabbro comprises the bulk of the Lick Fork body. The contact with the gabbro in the main body is distinct; however, in the west wall tongue, the gabbro appears to be gradational into the hornblende-gabbro. A foliation is observed which is attributable to alternating mafic-rich and felsic bands. These bands are about three cm in thickness (Figure 8c).

Textures are medium-grained, granoblastic-polygonal, and equigranular (Figure 8d). Plagioclase is usually highly altered to sericite, commonly as polygonal grains and is often embayed by pyroxenes. Smaller unaltered grains of plagioclase occur intergranular to hornblende.

Augite occurs as xenoblastic grains showing triple junctions and dihedral angles with adjacent phases. Some reaction of augite to hornblende occurs. Unlike the augite in the hornblende-peridotite, spinel inclusions are absent.

Orthopyroxene is polygonal, but coarser in size than orthopyroxene of the hornblende-peridotite or the gabbro. As in both of the other rock types, orthopyroxene in the hornblende-gabbro is altered along rims and fractures to chlorite and mica.

Biotite is reddish-brown in color and commonly occurs as medium size laths showing a preferred orientation. Undulose extinction and kink bands occur in the biotite, but the deformation of biotite is not as intense as in the hornblende-peridotite.

Whereas hornblende in the hornblende-peridotite is green-brown in color, that of the hornblende-gabbro is brown. This color variation is attributed to the higher Ti content (Binns, 1965). Generally, hornblende occurs as medium equigranular grains intergranular to the other silicate phases, and is often embayed by these phases.

Opaques occur in trace amounts as finely disseminated pyrite and pyrrhotite in association with the altered pyroxenes. Ilmenite is commonly associated with biotite, occasionally rimming the biotite.

Modal Analyses

The modal analyses summarized in Figure 9 (see Appendix A-III and Table B-1 for details) show a distinct variation in mineralogy among the three lithologies of the Lick Fork body. Olivine is restricted to the hornblende-peridotite zone, and plagioclase content decreases significantly from the gabbro to the hornblende-gabbro. Hornblende, a major phase of the hornblende-peridotite and the hornblende-gabbro, is absent in the gabbro.

The modal variation of clinopyroxene and plagioclase across the Lick Fork body is just the reverse of what should be expected for a normal differentiation trend; i.e., systematic decrease in mafic phases and increase in feldspars away from the basal ultramafic zone.

In addition to the silicate variation discussed above, it should be noted that the bulk of the sulfides and spinel phases is confined to the hornblende peridotite zone. Ilmenite, which only occurs in trace amounts in the hornblende-peridotite and the hornblende-gabbro, is a major oxide phase in the gabbro.

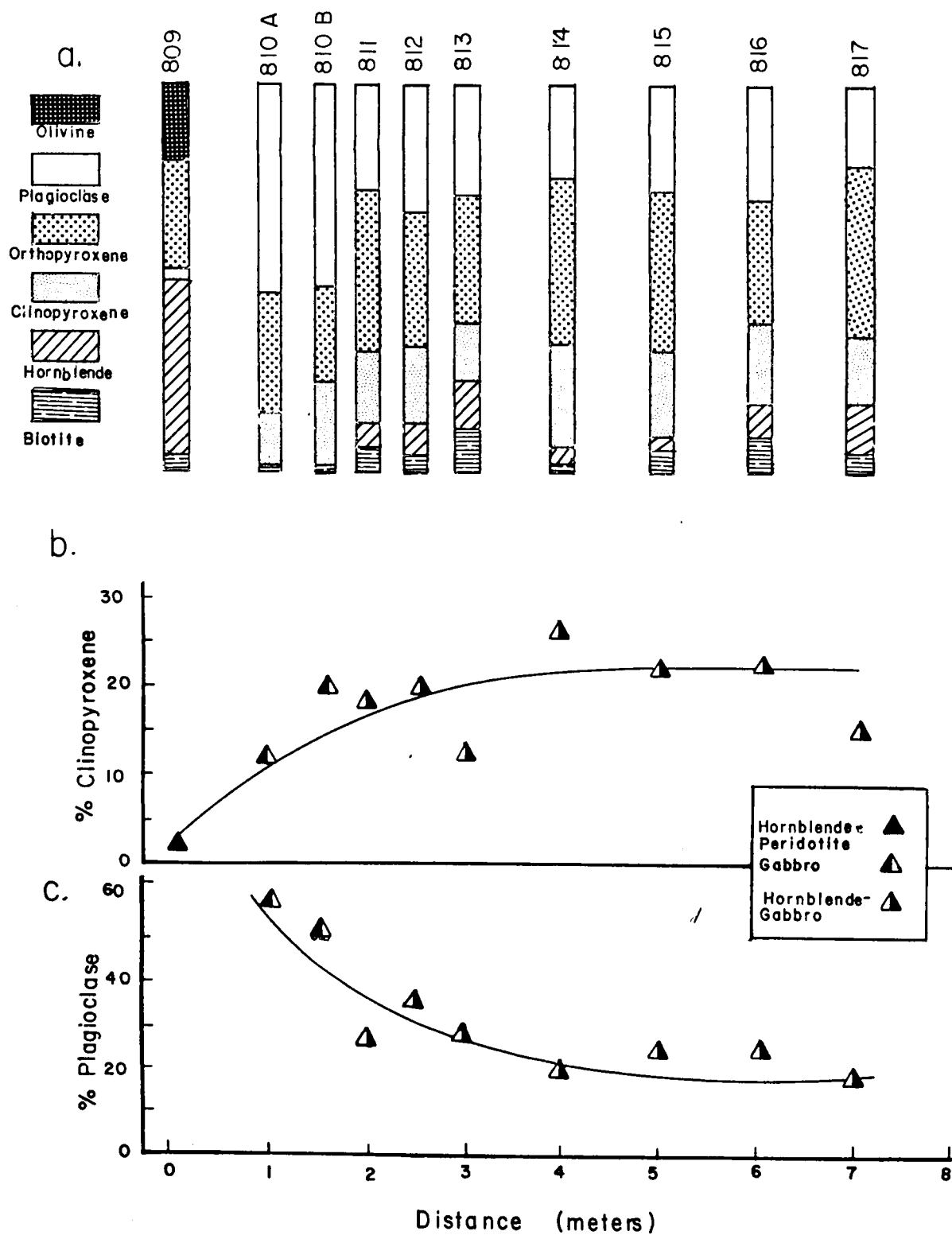


Figure 9. Variations in mineralogy across the Lick Fork body (traverse B-C, Figure 4, page 15). (a) Modal % silicates; (b) modal % clinopyroxene; (c) modal % plagioclase.

Silicate Chemistry

Representative electron microprobe analyses of olivine, clinopyroxene, orthopyroxene, plagioclase and hornblende compositions are plotted on Ca-Mg-Fe ternary along with Mg/(Mg+Fe) values for biotite and olivine (Figure 10). The clinopyroxene compositions ($\text{Wo}_{42-47}\text{En}_{40-45}\text{Fs}_{7-17}$) fall within the augite field in the pyroxene quadrilateral. No compositional zonation occurs within the individual grains; however, a slight variation occurs among clinopyroxenes in different samples.

Orthopyroxenes range in composition from En_{77} in the hornblende-peridotite zone to En_{60} in the gabbro. Ca content is consistently low for all orthopyroxenes (Wo_1). As with the clinopyroxene, orthopyroxene composition is homogenous within a single grain, but variation occurs among grains of different samples. The orthopyroxene is bronzite in the hornblende-peridotite, and hypersthene in the gabbro and the hornblende-gabbro (Deer, Howie and Zussman, 1966).

Hornblende compositions are $(\text{Na,K})_{.79-.86}\text{Ca}_{1.8}(\text{Mg,Fe}^{2+},\text{Mn})_{4.3} - (\text{Al,Ti})_{.7-.8}\text{Si}_{6.3}\text{Al}_{1.7}\text{O}_{22}(\text{OH})_2$. Based on $\text{Na}+\text{K}/\text{Al}^{\text{iv}}$ content, this amphibole is considered a pargasite (Deer, Howie and Zussman, 1966). The average Mg/(Mg+Fe) ratio varies from 0.79 in the hornblende-peridotite to 0.60 in the hornblende-gabbro. This composition is in the lower pargasite-upper hastingsite fields defined by Deer, Howie and Zussman (1966). The general parallelism of tie lines in Figure 10 suggests equilibrium among these mafic phases.

Feldspar compositions in the gabbro and the hornblende-gabbro vary from An_{57} to An_{40} . Although a variation in composition does occur among

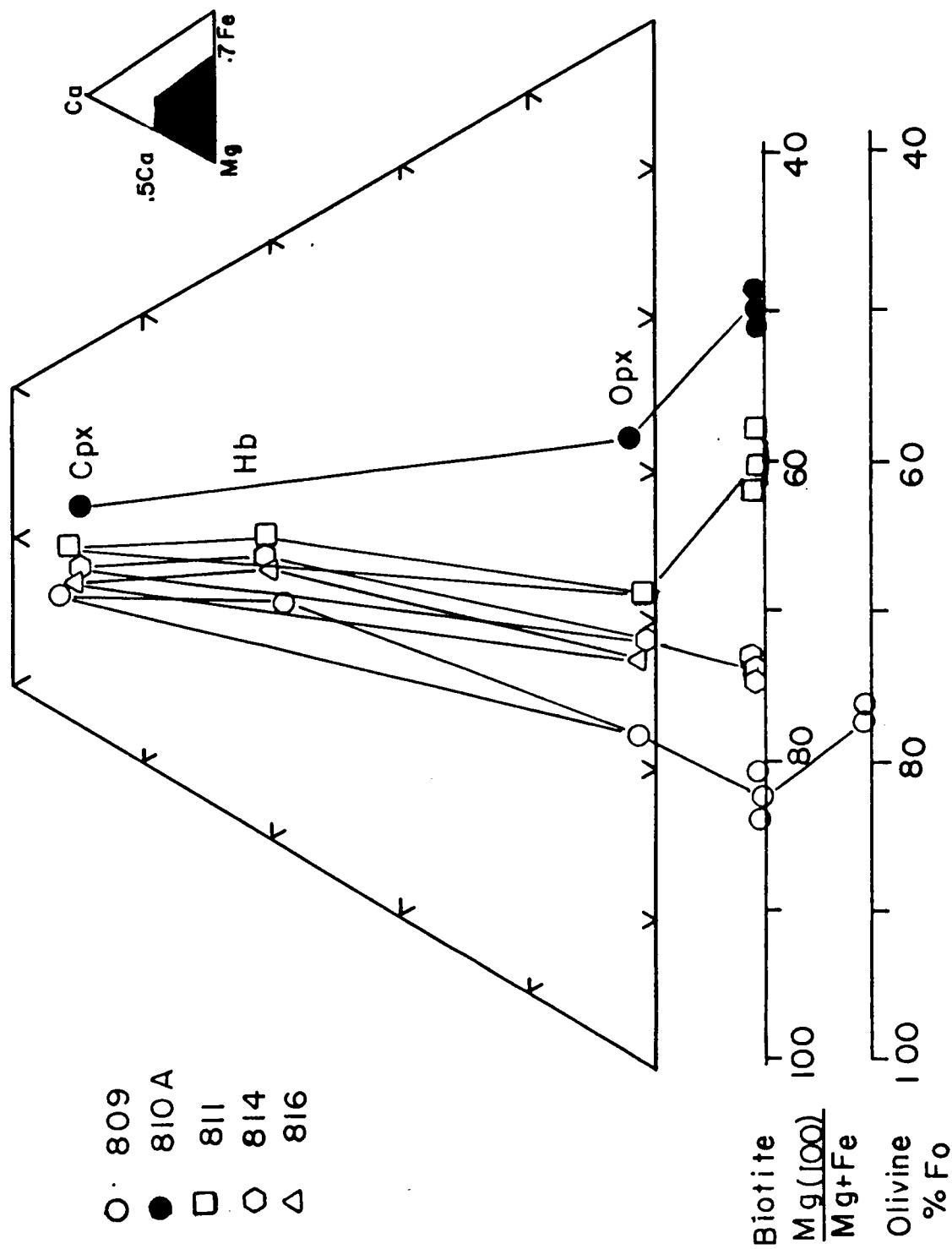


Figure 10. Compositions of the Lick Fork orthopyroxene (Opx), clinopyroxene (Cpx), hornblende (Hb), biotite and olivine plotted in a Ca-Mg-Fe ternary (mol %).

grains of a single sample, no zonation occurs within a single feldspar grain. The variation within a single sample is attributed to alteration of some feldspars.

Olivine, likewise, is unzoned. Average composition of the olivine is Fo_{77} .

Mg/(Mg+Fe) ratios for the mafic phases (biotite, clinopyroxene, orthopyroxene, and hornblende) and An% for the feldspars are plotted with respect to distance from the hanging wall on traverse B-C (Figure 11a-e). Mg-Fe variation is evident in all of the mafic phases. Mg content decreases from the hornblende-peridotite to the gabbro and then increases into the hornblende-gabbro zone. A progressive Mg enrichment in biotite and orthopyroxene is notable from the gabbro into the hornblende-gabbro. Mg content is noticeably higher in the assemblages containing hornblende. Also, Mg/(Mg+Fe) variation in the gabbro and the hornblende gabbro, like the modal variation discussed earlier, is opposite to the expected variation for a normal differentiation trend. In the feldspars, An content is low in the gabbro, and higher in the hornblende-gabbro.

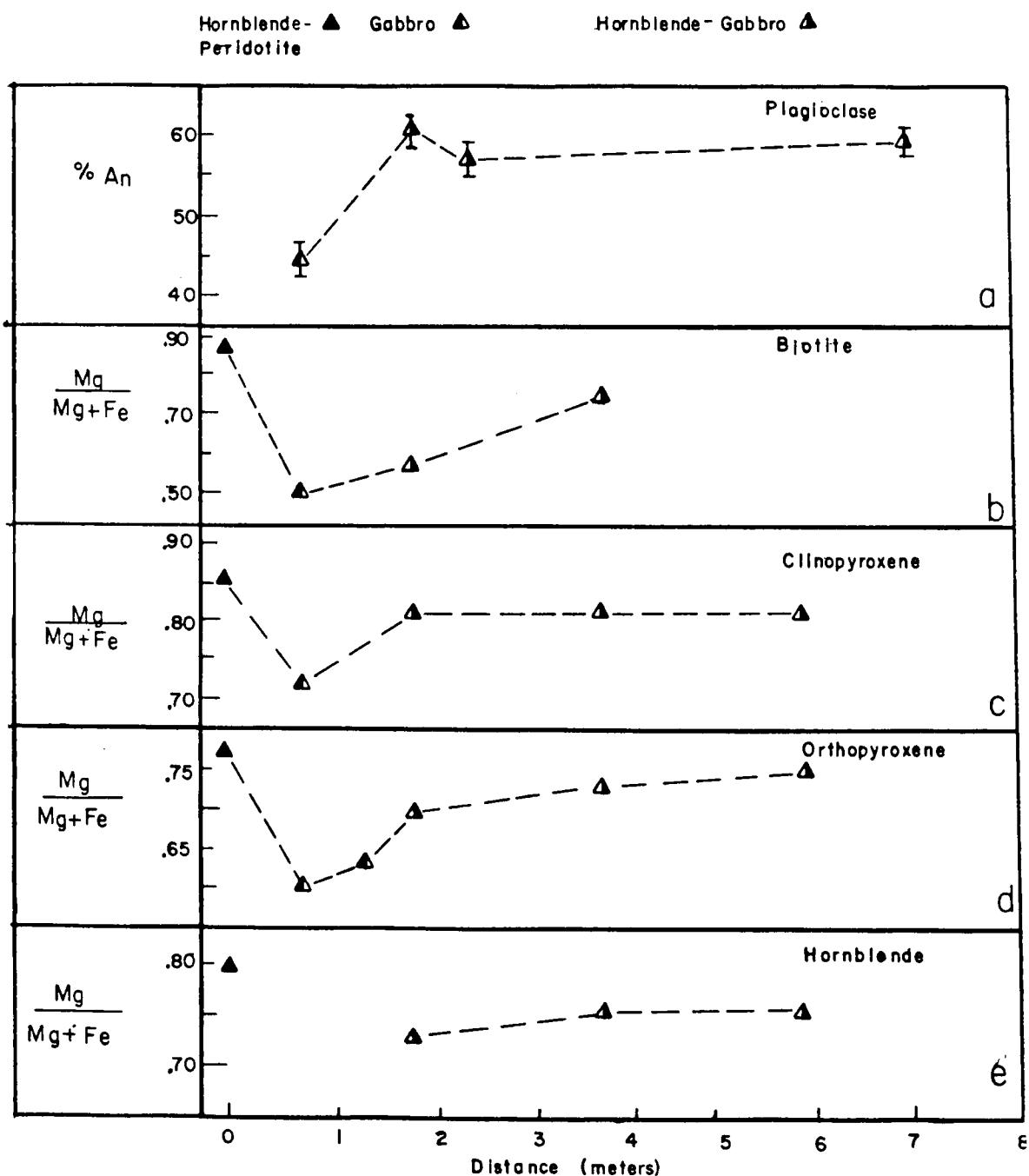


Figure 11. Compositional variations in coexisting mineral phases across the Lick Fork body (traverse B-C; Figure 3, page 14).

CHAPTER IV

SILICATE PETROGENESIS

Several features of the Lick Fork mafic body present problems in determining the condition of its formation. The mineralogy is common to both high-grade metamorphic and primary magmatic assemblages. Additionally, the pervasive polygonal textures occur in both metamorphic rocks (Spry, 1969) and in layered igneous intrusions such as the Stillwater Complex (Jackson, 1961). In the Gosse Pile layered intrusion, Australia, amoeboid olivine occurring intergranular to pyroxene has been interpreted by Moore (1973) and Goode and Moore (1975), as reflecting conditions of high pressure magmatic crystallization, whereby olivine crystallizes as a late phase intercumulate to early pyroxenes. Do similar textures in the Lick Fork body imply a similar petrogenesis, or is this a feature of metamorphism? Determination of either a magmatic and/or metamorphic origin requires applications of techniques beyond petrographic and field observations.

Evidence of Metamorphism

Several petrographic indicators based on silicate chemistry may be employed to ascertain the petrogenesis of the Lick Fork body.

Pyroxenes. Bhattacharyya (1971) has suggested that in a wt % ($\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3$) vs. Al_2O_3 plot, the field of igneous orthopyroxenes is separated from that of metamorphic orthopyroxenes by a line defined

by the equation $(\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3) + 0.775(\text{Al}_2\text{O}_3) = 44.04$. Although the Lick Fork orthopyroxenes contain no Fe^{3+} , such a plot for the Lick Fork orthopyroxenes along with the orthopyroxenes from other igneous and metamorphic rocks is shown in Figure 12. The Lick Fork orthopyroxenes fall in the metamorphic field close to the orthopyroxenes of the Strangways mafic granulites. The Gosse Pile orthopyroxenes (high pressure, magmatic crystallization) occur within the igneous region.

Kretz (1961,1963) demonstrated that $K_d^{\text{opx-cpx}}_{\text{d(Mg-Fe}^{2+})}$ ranges from 0.51-0.65 for metamorphic pyroxenes in charnockites and 0.65-0.73 for pyroxenes of igneous origin (see Appendix A-VII for discussion of K_d values). The $K_d = (\text{Mg}/\text{Fe})^{\text{opx}}/(\text{Mg}/\text{Fe})^{\text{cpx}}$ values of Saxena (1977) are 0.60 and 0.75 for pyroxenes from metamorphic rocks of charnockitic affinity and Stillwater, respectively. The $K_d^{\text{opx-cpx}}_{\text{d(Mg-Fe}^{2+})}$ as defined by Kretz (1961) and Ray and Sen (1970) was determined for the Lick Fork pyroxenes and compared to igneous and metamorphic pyroxenes of other occurrences (Figure 13). K_d for the pyroxenes in the Gosse Pile intrusion is about 0.88. This is higher than expected for normal layered intrusions but similar to that of peridotites (Moore, 1971). The Mecklenburg gabbro and metagabbro pyroxenes occur in their respective fields defined by their K_d 's. The K_d value for the Lick Fork pyroxenes vary from 0.480-0.653 with an average $K_d = 0.570$. This is within the range of metamorphic pyroxenes.

Amphiboles. Amphibole compositions may be useful in determining the origin of mafic rocks. Leake (1965) suggested that igneous or metamorphic

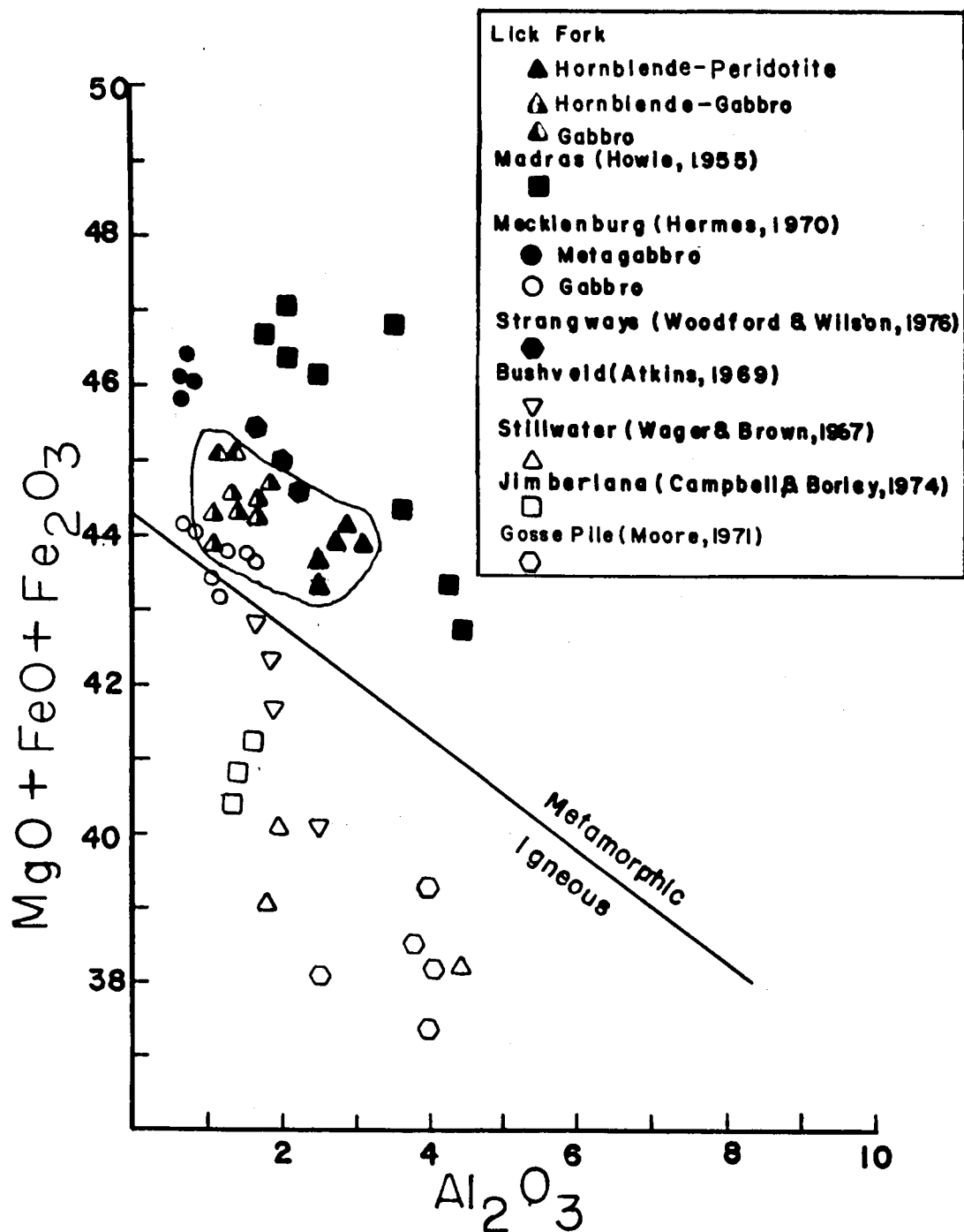


Figure 12. Weight percent $\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3$ vs. Al_2O_3 plot for orthopyroxene of the Lick Fork body and igneous and metamorphic orthopyroxenes from other occurrences. The boundary separating igneous from metamorphic pyroxenes is from Bhattacharya (1971).

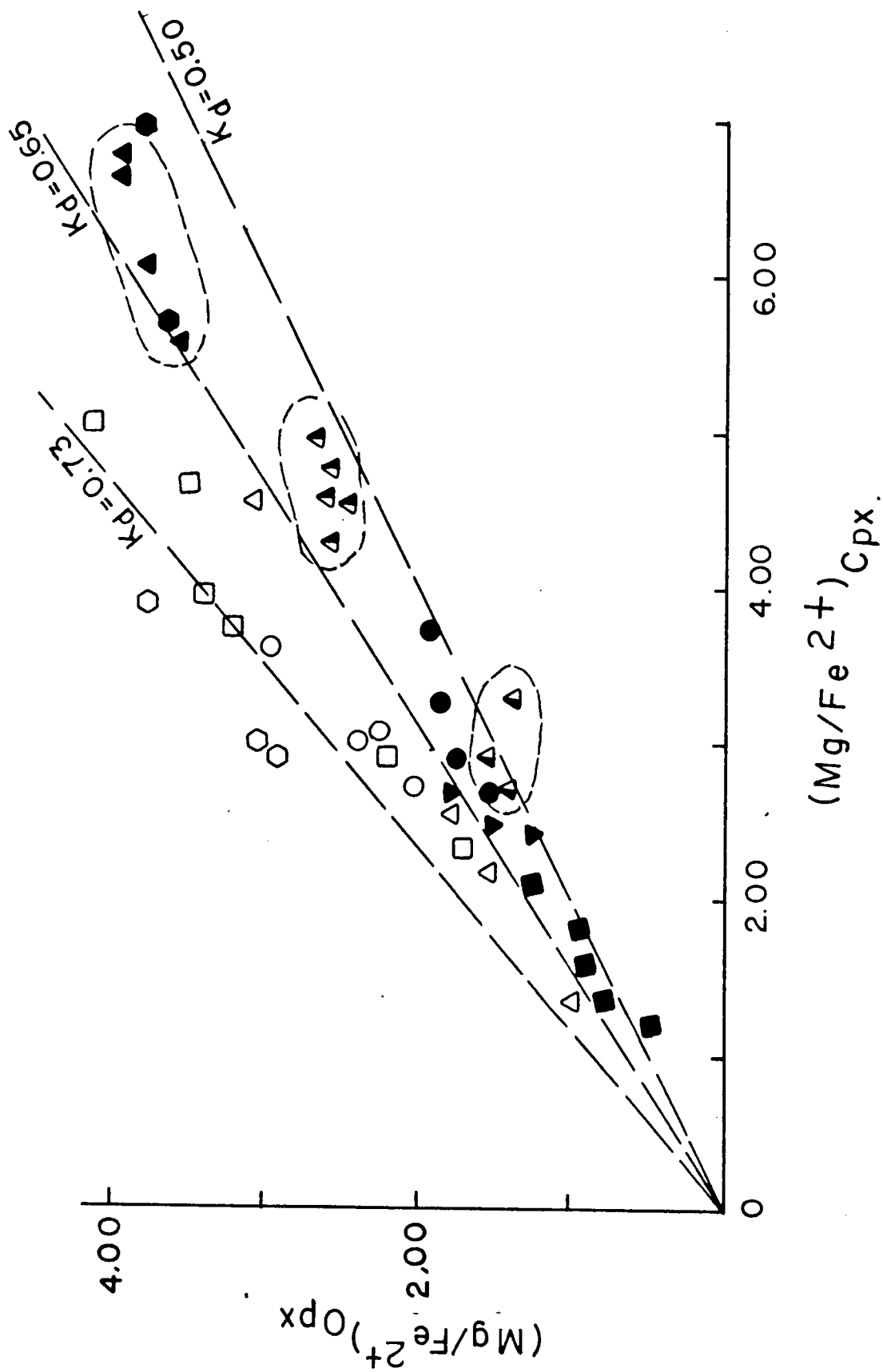


Figure 13. $K_d^{Opx-Cpx}$ for the Lick Fork pyroxenes, and metamorphic and igneous pyroxenes from other sources. Symbols same as Figure 12.

amphiboles could be discriminated on the basis of their $\text{Al}^{\text{iv}}/\text{Si}(\text{Al}^{\text{iv}})$ ratios, and Raase (1974) found an increase in Al^{iv} with increasing metamorphic grade. Comparing $\text{Al}^{\text{iv}}/\text{Al}^{\text{vi}}$ ratios for metamorphic and igneous amphiboles, Fleet and Barnett (1978) concluded that igneous amphiboles have an $\text{Al}^{\text{iv}}/\text{Al}^{\text{vi}} \leq 3.3$. Although chemical composition of metamorphic amphibole is more dependent upon whole rock composition than temperature and pressure of metamorphism, Fleet and Barnett (1978) suggests that Al^{vi} appears to increase with increasing pressure in regionally metamorphosed terrains, and that $\text{Al}^{\text{iv}}/\text{Al}^{\text{vi}}$ ratio of 2.0 is equivalent to Raase's (1974) 5kb boundary.

In Figure 14, $\text{Al}^{\text{iv}}/\text{Al}^{\text{vi}}$ ratios of the Lick Fork amphiboles occur in a broad field around the 3.3 isopleth, similar to the amphiboles of Broken Hill Australia (Binns, 1965). The Lick Fork amphiboles of ultramafic association occur in the metamorphic field whereas the amphiboles of the mafic lithologies fall into the igneous region. $\text{Al}^{\text{iv}}/\text{Al}^{\text{vi}}$ ratios of the Mecklenburg gabbro and metagabbro occur as two distinct fields in the igneous amphibole region. However, as discussed earlier, $K_{\text{d}(\text{Mg-Fe}^{2+})}^{\text{opx-cpx}}$ in pyroxenes in the Mecklenburg metagabbro is consistent with a metamorphic origin (Figure 13). This broad overlap is attributed to chemical constraints imposed upon $\text{Al}^{\text{iv}}/\text{Al}^{\text{vi}}$ ratios, thereby limiting its utility as a precise pressure indicator. Spread of Al^{iv} and Al^{vi} contents reflect variation in whole rock composition, which in turn, influences the amount of Al, Fe^{3+} and Ti in the octahedrally coordinated M position (Fleet and Barnett, 1978). $\text{Al}^{\text{iv}}/\text{Al}^{\text{vi}}$ ratios, therefore, may not unequivocally

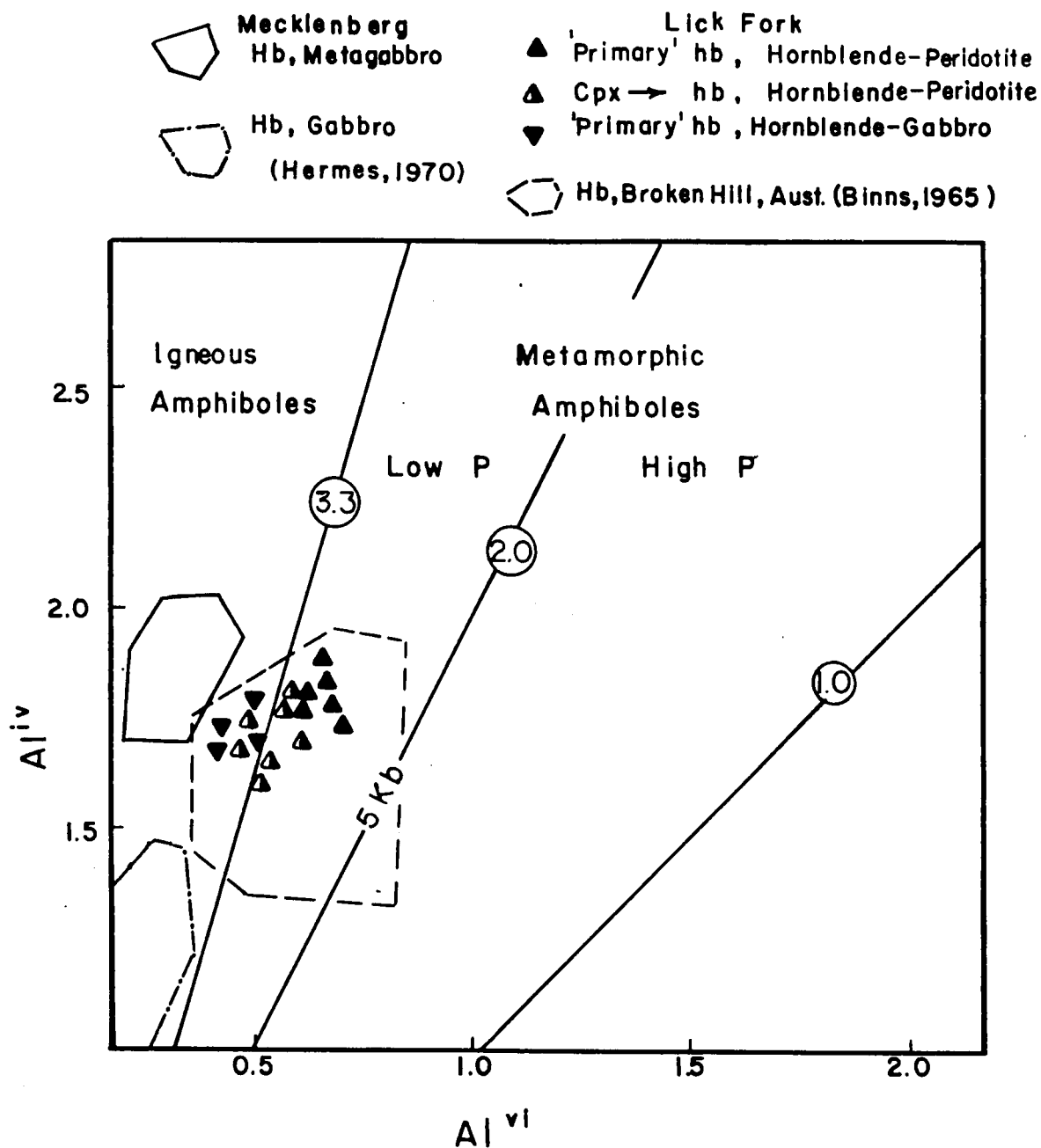


Figure 14. Comparison of the Al^{iv}/Al^{vi} ratios of the Lick Fork amphiboles with some igneous and metamorphic amphibole compositions (modified from Fleet and Barnett, 1978).

discriminate between igneous and metamorphic amphiboles. Distribution of $\text{Al}^{\text{iv}}/\text{Al}^{\text{vi}}$ in the Lick Fork amphiboles appears to be a function of whole rock composition, yet the similarity to the Broken Hill amphiboles suggests a metamorphic origin at a pressure less than 5 kb.

Increasing Ti content (Binns, 1965; Bard, 1970; and Raase, 1974), and increasing alkali content of amphiboles (Binns, 1965; Bard, 1970) have been correlated with increasing metamorphic grade. In terms of Ti contents the amphiboles of the Lick Fork ultramafic assemblages (average 0.103 Ti) appear to lie between the values reported for lower amphibolite and upper amphibolite metamorphic facies, whereas amphiboles from the mafic assemblage are comparable to the values for hornblende-granulite metamorphic facies (Table 2).

Table 3 compares $(\text{Na} + \text{K})_{\text{total}}/(\text{Na} + \text{K})_{\text{total}} + \text{Ca}$ ratios of the Lick Fork amphiboles to those of the progressive metamorphic terrain in Arecena, Spain (Bard, 1970). Ratios for the Lick Fork ultramafic and mafic amphiboles are 0.305 and 0.315, respectively. These values compare well to the hornblende-orthopyroxene zone of the Arecena metamorphic terrain, which has experienced hornblende-granulite facies metamorphism.

A systematic decrease in $K_d^{\text{cpx-hb}}_{\text{d}(\text{Mg-Fe}^{2+})}$ with corresponding increase in metamorphic grade has been noted by Kretz and Jen (1978). K_d for calcic pyroxene-hornblende pairs decrease from 1.7 for upper amphibolite facies to 1.6 for transitional amphibolite facies, and varies from 1.5-1.3 for hornblende granulites. Average K_d 's for Lick Fork cpx-hb pairs vary from 1.747 in the ultramafic assemblage to 1.522 in the

TABLE 2
AVERAGE TITANIUM CONTENTS OF LICK FORK AMPHIBOLES
COMPARED TO THOSE OF OTHER
METAMORPHIC TERRAINS

Metamorphic Facies	Maximum	Minimum	Average	No. of Samples
<u>Amphiboles Analyzed by Raase (1974)</u>				
Greenschist-amphibolite				
transition	.080	.020	.048	18
Lower amphibolite	.130	.030	.082	51
Upper amphibolite	.220	.060	.151	38
Hornblende-granulite	.300	.150	.236	53
<u>Lick Fork Hornblende-Peridotite</u>				
"Primary"	.081	.147	.103	17
"Secondary"	.116	.132	.123	6
Lick Fork hornblende- gabbro	.328	.224	.291	29

TABLE 3
COMPARISON OF THE ALKALI CONTENT OF LICK FORK
AMPHIBOLES AND ARACENA, SPAIN AMPHIBOLES

Metamorphic Grade	$\frac{(\text{Na}+\text{K})_{\text{total}}}{(\text{Na}+\text{K})_{\text{to 1 + Ca}}}$			
Amphiboles analyzed by Bard (1970)				
Greenschist (B ₁)			0.09 — 0.18	
Cordierite-amphibolite (B ₂)			0.15 — 0.28	
Hornblende-orthopyroxene (B ₃)			0.19 — 0.30	
Lick Fork Hornblende-Peridotite	<u>Maximum</u>	<u>Minimum</u>	<u>Average</u>	<u>No. of Samples</u>
"Primary"	.332	.295	.305	17
"Secondary"	.326	.261	.309	6
Lick Fork hornblende-gabbro	.292	.328	.315	29

mafic assemblages (Appendix Table A-1). This suggests an upper amphibolite to hornblende-granulite facies metamorphism. According to the tentative geothermometer proposed by Kretz and Jen (1978), the $K_{d(Mg-Fe^{2+})}^{cpx-hb}$ values of the Lick Fork ultramafic and mafic assemblages indicate equilibration temperatures of about 600°-750°C.

As discussed earlier, there are two textural varieties of hornblende in the ultramafic assemblage. Type 1 ("primary" hornblende) is a coarse grain polygonal hornblende; type 2 ("secondary" hornblende) is a reaction product of clinopyroxene. From a comparison of their Ti contents (Table 2) as well as their overall compositions (Appendix Table B-5), it is evident that the two varieties of hornblende have equilibrated to the same P-T conditions and, therefore, probably represent the same metamorphic event. According to Bhattacharyya (1974) such $Cpx \rightarrow Hb$ alteration textures are brought about by volatile fluids produced at the peak of granulite metamorphism.

The Lick Fork mafic, ultramafic and pyroxene-syenite assemblages are depicted in Ca-Si-(Fe+Mg) ternary diagrams (Figure 15). All assemblages of the Lick Fork body and the pyroxene-syenite country rocks are compatible with granulite facies metamorphism. Although texturally augite appears to be altering to primary hornblende, no crossing tie lines are observed, thereby supporting earlier conclusions of equilibrium conditions.

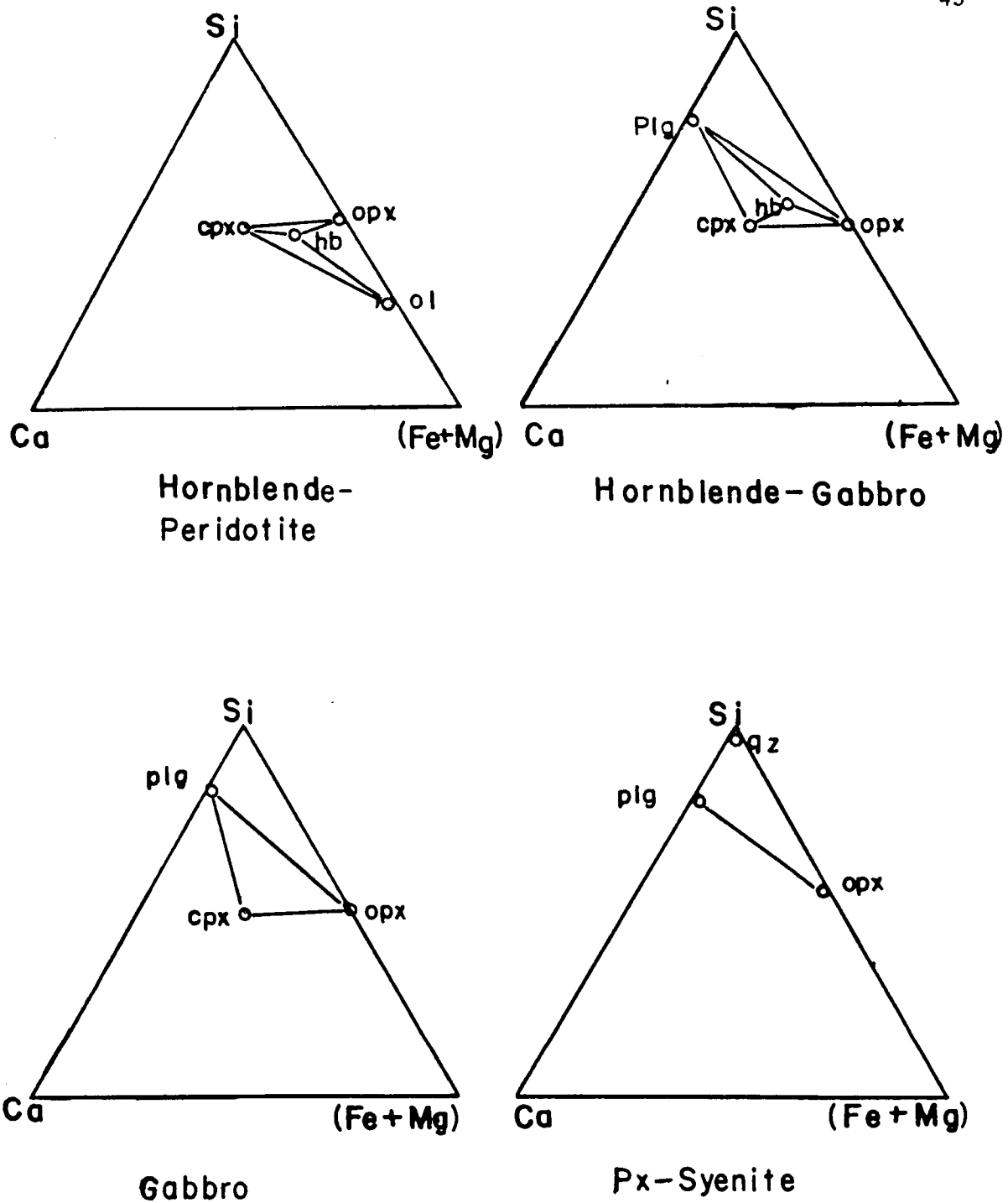


Figure 15. Si-Ca-(Fe+Mg) ternary plot of the Lick Fork body and country rock lithologies.

Deformation Features

The textures and structure of the Lick Fork body shows several features suggestive of tectonic deformation. These have been discussed in the petrography section and are summarized below:

1. Biotite is usually highly deformed showing well developed kink bands. This is true particularly in the ultramafic zone.
2. Hornblende often exhibits undulose extinction.
3. Plagioclase exhibits deformation in the form of spindle-shaped albite twins.
4. Pyroxenes often show undulose extinction and twinning lamellae.
5. Mortar texture occurs in the pyroxene-syenite at the hanging wall contact.

The deformation appears to be later than the main metamorphic event because all the silicate phases bear the imprint of deformation. The more intense deformation seems to be localized in the ultramafic unit and pyroxene-syenite adjacent to the hanging wall contact, suggesting that this contact may be a fault plane.

Hydrothermal Alteration

Evidence of hydrothermal alteration is indicated by the presence of altered orthopyroxene and feldspar in the hornblende-bearing assemblages. Sericitization and uraltization of orthopyroxene are common in the host rock assemblages. Feldspar is generally sericitized and calcite is associated with hornblende. The alteration is not as intense in the gabbro as it is in the hornblende-bearing

lithologies, particularly the ultramafic unit. The alteration features are probably due to selective migration of hydrothermal fluids along fractures in the Lick Fork body. Serpentinization may have been the result of hydration of olivine by volatiles released at peak metamorphism as discussed by Moeskops and Davis (1977) in the Kambalda Ni district, Australia. However, in the Lick Fork body, there is little evidence that serpentinization is pre-deformational. Also, in many samples, serpentinization of olivine is very slight, particularly in sulfide-barren zones. In fact, in many cases, olivine is serpentinized only where it is in contact with sulfides. It is concluded that serpentinization is also the result of hydrothermal processes along selected fractures in the Lick Fork body. Alteration of pyroxenes to clay minerals in the more weathered samples are indicative of the influence of surficial weathering upon the lithologies.

Evidence of Magmatism

The cross-cutting relationships of the mafic lithologies to the pyroxene-syenite country rock are indicative of emplacement as an intrusive body.

The variation diagram in Figure 16 shows a systematic increase in modal percent of the mafic minerals (opx+cpx+bt+hb+ol) with increasing $Mg/(Mg+Fe^{2+})$ ratios in orthopyroxene. To envisage such a systematic variation under processes of metamorphic differentiation is difficult, but such a trend would be expected from processes of magmatic differentiation.

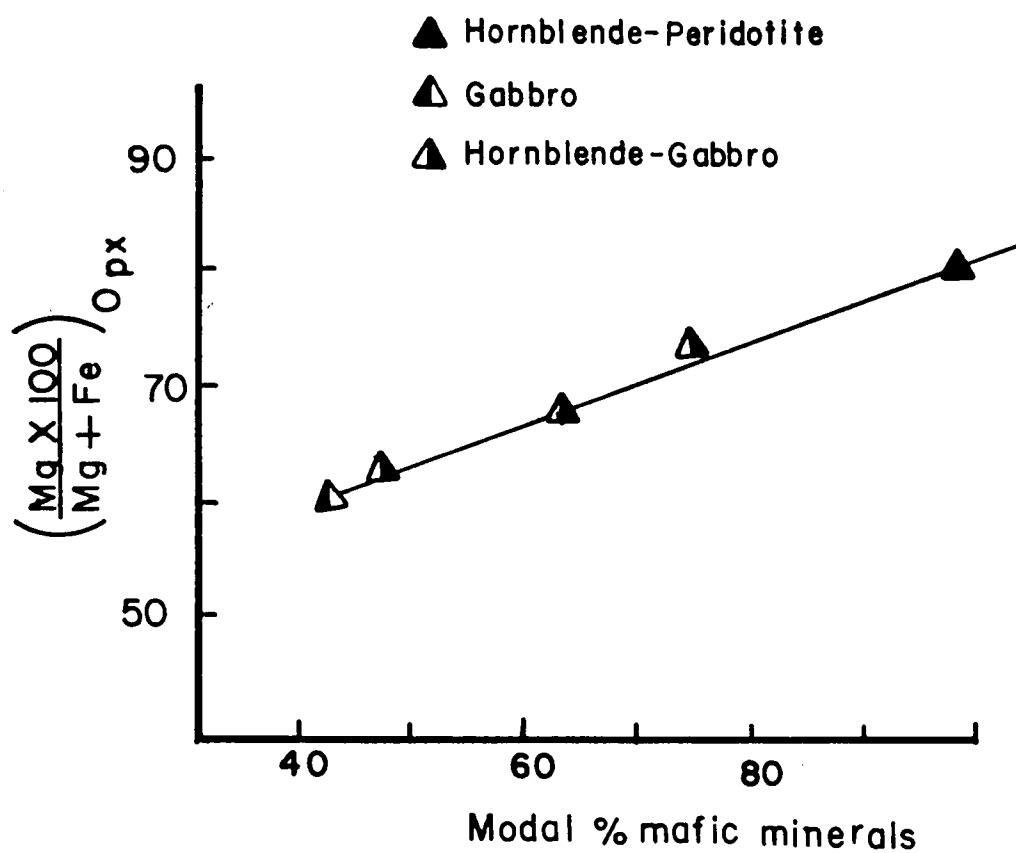


Figure 16. Modal % mafic minerals vs. $\frac{(\text{Mg} \times 100)}{(\text{Mg} + \text{Fe})}$ Opx in the Lick Fork body.

Discussion

Petrologic features of the Lick Fork lithologies are summarized in Table 4. Evidence indicates the Lick Fork body is orthometamorphic in origin, and has probably equilibrated to granulite facies metamorphism. DeWaard (1965) defined two granulite subfacies based on the appearance of amphiboles. The hornblende-granulite subfacies is considered to be transitional from amphibolite to hypersthene grade (pyroxene-subfacies). Mineralogically, two assemblages corresponding to these subfacies exist in the Lick Fork body. These are: (1) the peridotite and the hornblende-gabbro units and (2) the hornblende-free gabbro unit. The absence of prograde reaction textures and parallelism of compositional tie lines suggest both assemblages are in equilibrium. It is unlikely, therefore, that the highly variable P-T conditions necessary to produce two such subfacies existed in the Lick Fork body. How, then, do the hornblende bearing and the non-hornblende assemblages remain in equilibrium under limited P-T conditions? Does the absence of prograde reaction textures preclude the possibility of a prograde event? Also, it has been shown that the chemical variation is attributed to magmatic differentiation. Is there an explanation for the unusual Mg enrichment trend?

Prograde metamorphism and equilibrium conditions. According to Sen and Ray (1971), the compositions of metamorphic hornblendes of granulite facies correspond to mixtures of:

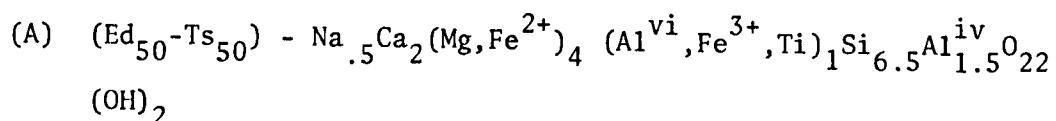
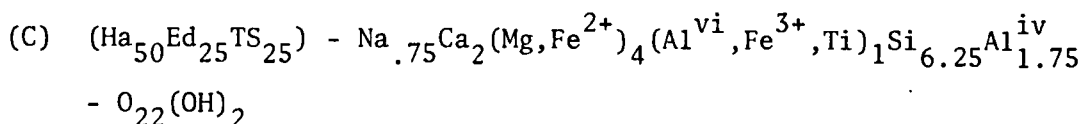
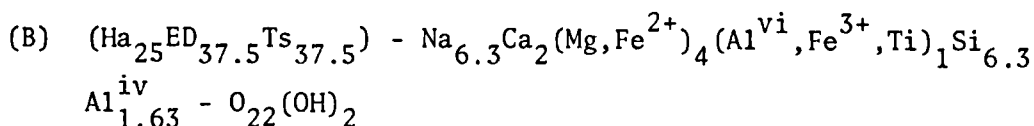


TABLE 4
SUMMARY OF LICK FORK LITHOLOGIES

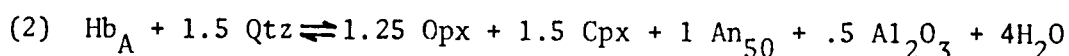
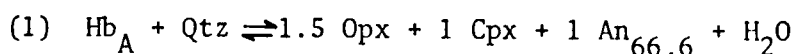
Lithology	Hornblende- Peridotite	Gabbro	Hornblende- Gabbro
Mineralogy			
Silicates	Hb-Opx-Ol-Cpx-Bt	Plag-Opx-Cpx-Bt	Plag-Cpx-Opx-Hb-Bt
Secondary	Uralite-serpentine	Uralite-sericite (tr)	Uralite-sericite
Sulfides	po-pn-ms-cpy-vl	po-cpy (tr)	po-cpy (tr)
Oxides	Spinel (pleonaste)- mt-ilm	ilm-ht	mt-ht
Silicate Textures			
Primary	Polygonal-equigranular, granoblastic, med grain w/intergranular finer grain Opx and Ol	Polygonal equigranular, granoblastic, med grain Plag-Cpx-Opx	Polygonal equigranular, granoblastic, med-coarse grain, Plag-Cpx-Opx-Hb, foliated Bt
Reaction texture	Cpx → hb	Absent	Cpx → hb
Hydrothermal Alteration	Opx → uralite, serp. Ol → serp.	Opx → uralite (weak)	Plag → sericite Opx → uralite
Tectonism	Strongly evident (post granulite)	Weak	Weak

TABLE 4 (continued)

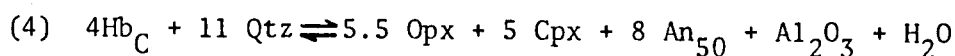
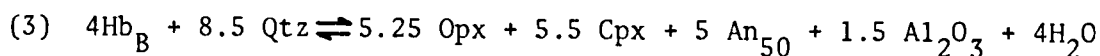
Lithology	Hornblende- Peridotite	Gabbro	Hornblende- Gabbro
Chemistry			
Mg/(Mg+Fe)	Ol 0.77		
(Mafics)	Bt 0.88	Bt 0.53	Bt 0.60-0.75
	Cpx 0.87	Cpx 0.72	Cpx 0.81-0.82
	OpX 0.78	OpX 0.59-0.63	OpX 0.69-0.72
	Hb 0.79	Hb Absent	Hb 0.73-0.76
%An (Feldspars)		An ₄₃₋₄₆	An ₅₇₋₆₃
K _d (Mg-Fe ²⁺)	OpX-Cpx .582	OpX-Cpx .537	OpX-Cpx .588
	OpX-Hb 1.044	---	OpX-Hb .903
	Cpx-Hb 1.747	---	Cpx-Hb 1.495
	OpX-Bt .689	OpX-Bt 1.442	OpX-Bt .887



For composition (A) the following reactions are probable in nature:

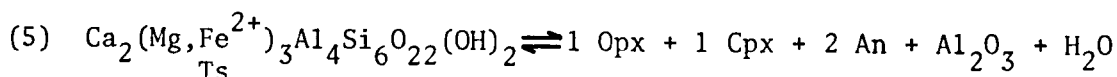


The possible reactions for compositions between (B) and (C) are:



In these cases, excess alumina may be incorporated into the pyroxene structures. The Lick Fork hornblendes are roughly equivalent to composition (C).

All of these reactions involve the incorporation of free quartz, but the Lick Fork assemblages do not contain quartz. One reaction discussed by Sen and Ray (1971) which does not involve excess quartz is:



It is possible, therefore, that the reaction of $\text{Hb} \rightleftharpoons \text{Opx} + \text{Cpx} + \text{An} + \text{H}_2\text{O}$ may occur in a quartz deficient environment such as the Lick Fork gabbro.

For theoretical breakdown reactions for natural hornblendes in granulite facies metamorphism described above, Sen and Ray (1971) have established the following criteria concerning the reaction products:

1. Theoretical Opx-Cpx ratios in the reaction products of hornblende dehydration, range from 0.8-1.1.

In the natural assemblages discussed by Sen and Ray (1971) about half occur in this range. The range for natural assemblages are more variable, 0.3-2.3 for mafic charnockites in Madras India (Subramanian, 1959), and 0.7-2.0 for those of the Willyama complex Australia (Binns, 1965). Opx-Cpx ratios for the Lick Fork assemblages vary from 1.1-2.8 with an average ratio of 2.03. The Lick Fork values are higher than the calculated ratios, but are close to those of natural reaction assemblages.

2. The optimum An content for the plagioclase is An_{50} , however plagioclase compositions may be in the andesine range in natural mafic granulites due to the reaction with earlier amphibolite-grade plagioclase.

Plagioclase compositions in the Lick Fork body range from An_{43} to An_{60} with an average of An_{53} . This composition is in close agreement to the theoretical composition of feldspar derived from hornblende breakdown reactions.

An additional argument for prograde metamorphism is shown in the comparison of $Mg/(Mg+Fe)$ for coexisting hornblende, orthopyroxene, clinopyroxene and olivine in the hornblende-peridotite, and hornblende-gabbro (Table 5).

For the samples depicted in Table 5, hornblende $Mg/(Mg+Fe)$ is intermediate to its complimentary pyroxene pair. Sen (1970) has postulated that in reactions involving the formation of Cpx-Opx from the dehydration of amphiboles, the amphibole $Mg/(Mg+Fe)$ is intermediate to the coexisting pyroxenes. Comparison of the chemistry and mineralogy

of the Lick Fork assemblages to that derived from the theoretical breakdown of hornblende to granulite facies suggests prograde metamorphism.

TABLE 5
AVERAGE Mg/(Mg+Fe) FOR COEXISTING MAFIC SILICATES,
LICK FORK BODY

Sample	D-1	809	810A	811	814	816
Ol	.775					
Opx	.786	.788	.599	.696	.726	.724
Hb	.793			.729	.753	.758
Cpx	.867	.856	.733	.821	.825	.814
Bt		.847	.538	.599	.749	

It can be seen from Table 4, pages 50-51, that hornblende occurs only in lithologies with higher Mg content. Also, Ti content and $K_{d(Mg-Fe)}^{Hb-Cp}$ values of ultramafic hornblendes are indicative of a lower grade (amphibolite) metamorphism, whereas those of the hornblende-gabbro are more characteristic of hornblende-granulite metamorphism.

Sen (1970) postulates that the stability of amphibole increases with increasing Mg content. Experiments of amphibole stabilities under variable f_{O_2} -T conditions (Popp et al., 1977a) show that with increasing T (and f_{O_2}) the stability field of amphibole increases with increasing Mg content. However, as mentioned earlier, highly variable P-T conditions are unlikely to have existed under granulite equilibrium conditions. It is suggested, therefore, that the stability of the Lick Fork assemblages is a function of Mg-Fe content of the parent hornblendes, and not a product of variable P-T conditions.

Nature of variation. As discussed earlier, the observed compositional and modal variations are uncharacteristic of typical magmatic differentiated sequences. Because of the size limitations of the exposure studied, and the possible effects of metamorphism on the element distribution in the body, this variation is poorly understood.

Field observations do not completely support a single stage intrusive model. In the west wall apophyse, the gossan seam (hornblende-peridotite) is enclosed in pyroxene-syenite, and is nowhere in contact with the gabbro. This is also true of the east wall exposure at the southern extremity (Figure 4c, page 15). In addition, sharp compositional variations, such as those encountered from the hornblende-peridotite to the gabbro, have been argued as evidence for multiple intrusion (Wager and Brown, 1968). Therefore, the Lick Fork mafic-ultramafic lithologies may have originally resulted from an episode of multiple injections of melts of mafic and ultramafic composition. The body then underwent granulite-facies metamorphism. Some reactions occurred at peak metamorphism by the volatiles generated from the dehydration processes of the primary hornblendes. These volatiles reacted with clinopyroxene to form hornblende. Later faulting at the hanging wall contact provided the conduits for hydrothermal alteration of primary silicates.

CHAPTER V

SULFIDE MINERALIZATION

Mineralogy and Textures

Most of the sulfides in the Lick Fork body are confined to the hornblende-peridotite. In this unit the sulfides comprise 20-30% of the rock. In contrast, only traces of sulfides occur in the hornblende-gabbro. Also, fine disseminated sulfides (predominantly pyrrhotite, with some chalcopyrite) are observed in the country rock near the orebody.

Sulfide assemblages in the hornblende-peridotite consist of pyrrhotite (po), marcasite (ms), pentlandite (pn), violarite (vl), chalcopyrite (cpy), and pyrite (py). Sulfide stringers and disseminations form a "net" texture exhibiting weak foliation. Within the sulfide matrix are occluded grains of primary silicates. In the gabbro and the hornblende-gabbro, pyrrhotite and chalcopyrite occur as fine disseminations in the alteration products of the primary silicates. Occasionally, pyrrhotite is present as rounded blebs in hornblende.

Oxide minerals comprise about 2-5% of the hornblende-peridotite and the gabbro but only trace amounts of the hornblende-gabbro. The oxide phases of the hornblende-peridotite are green spinel (pleonaste; p), magnetite (mt), ilmenite (ilm), rutile, and geothite. In the gabbro, the oxides are comprised of ilmenite-hematite (ht). Like the silicates in the gabbro, the ilmenite is polygonal granoblastic, equigranular. Hematite occurs as fine exsolved blebs in the ilmenite. The equigranular-polygonal texture of both the oxides and silicates in this unit suggests

a common origin for both. Oxides and silicates in the gabbro were probably formed during the same metamorphic event (granulite facies). Oxides in the hornblende-gabbro are finely disseminated. Magnetite is commonly associated with the disseminated sulfides. Rutile occurs as fine asterisks in biotite cleavage and ilmenite rims oxidized biotite. Unlike oxides of the gabbro, those of the hornblende-gabbro are not a product of granulite-facies metamorphism, but are probably the result of oxidation conditions during post-metamorphic alteration of the primary silicates. The features of the opaque phases are summarized in Table 6.

Since the sulfides are confined primarily to the hornblende-peridotite unit, discussion of the opaque phases will be limited to sulfides and oxides of this zone. Enlargement of a hornblende-peridotite thin section (Figure 17) shows "net" textured sulfides (Naldrett, 1969) confined primarily to zones of finer-grained anhydrous silicates, whereas, the areas of coarser grained hornblende remain essentially barren. Also, ragged islands of silicate fragments occur within the sulfide matrix (Figure 17), some of which are in optical continuity. Biotite islands in the sulfide matrix are highly contorted, randomly oriented (Figure 18b), and often corroded (Figure 18c). Foliation of the sulfides is parallel to regional trend. Hornblende-sulfide grain boundaries and biotite-sulfide grain boundaries are contiguous (Figure 18d), whereas, a selvage of serpentine, mica, or chlorite usually separates anhydrous silicates from sulfide grain boundaries. This selvage is usually discontinuous (Figure 18e), but well-formed euhedral laths of

TABLE 6
SUMMARY OF LICK FORK SULFIDES AND OXIDES

Lithology	Hornblende- Peridotite	Gabbro	Hornblende- Gabbro
Modal % sulfides	20-30%	Trace	Trace
Modal % oxides	2-5%	2-3%	Trace
Sulfide phases (order of abundance)	po-ms-vl-py-cpy-pn-bn-mk	po-cpy	po-cpy-py-pn
Oxide phases (order of abundance)	sp-mt-ilm-goethite- rutile	ilm-ht	mt-ilm-rutile
Oxide textures	Spinel--intergranular to silicates.	ilm--polygonal grano- blastic, equigranular with silicates.	mt--associated with sulfides.
	mt-- disseminated vein- lets in serpentine. Stringers in po. Rimming spinel.	ht--elongated blebs in ilm.	Rutile--asterisks in biotite.
	ilm--blebs in mt.		ilm--rims in Bt.
	Goethite--in fractures.		
	Rutile--asterisks in Bt.		

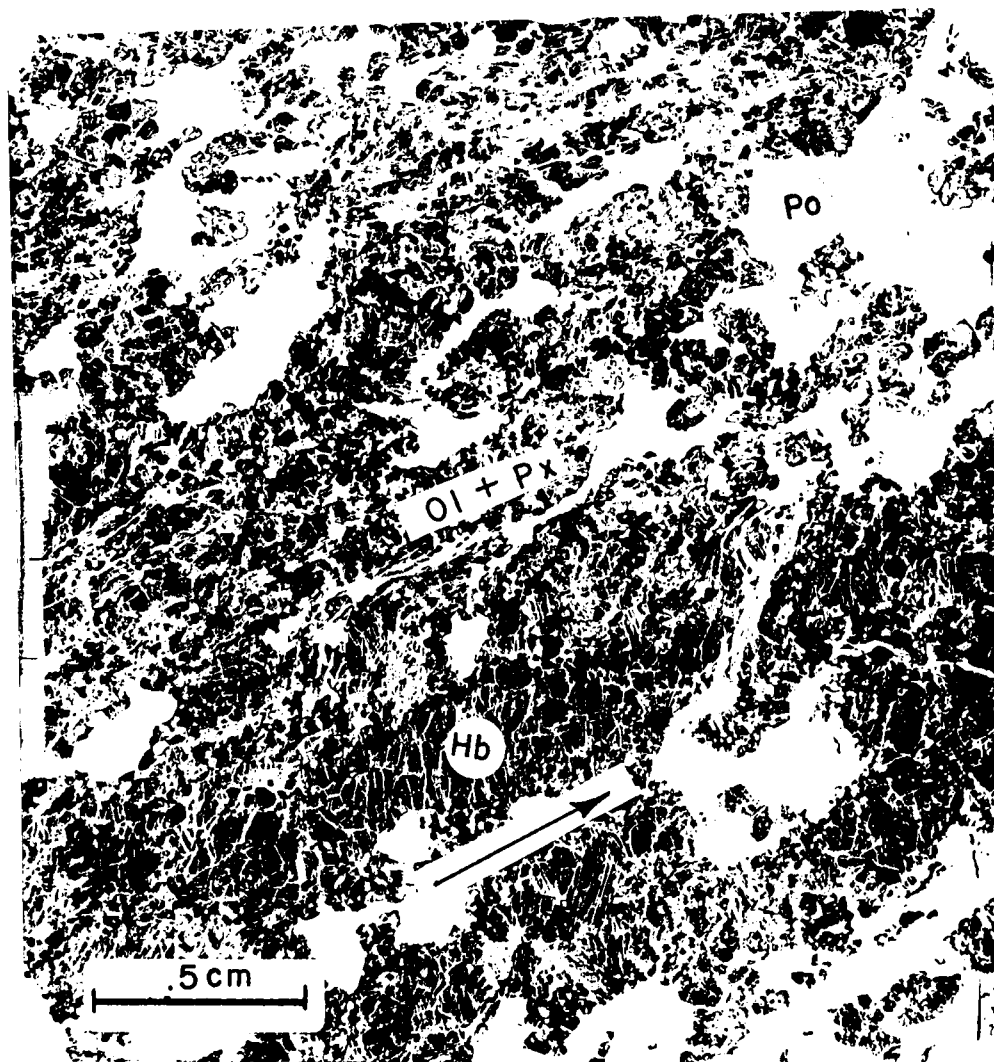
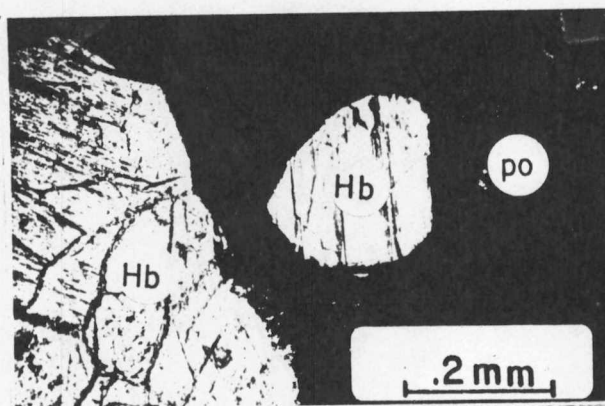


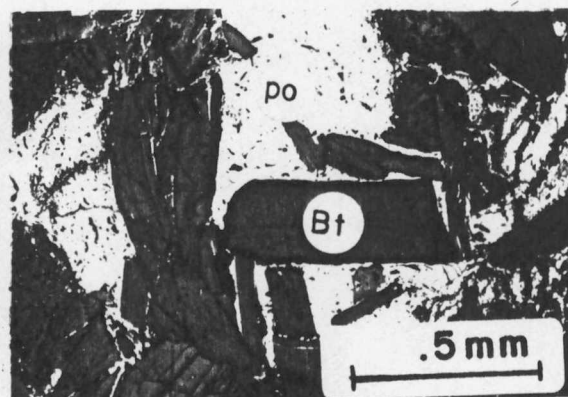
Figure 17. Enlargement of hornblende-peridotite thin section, sulfide-silicate textures. Arrow indicates direction of foliation of country rock. Note barren hornblende zone and ragged silicate islands in sulfide matrix.

Figure 18. Sulfide-silicate textures in the hornblende-peridotite.

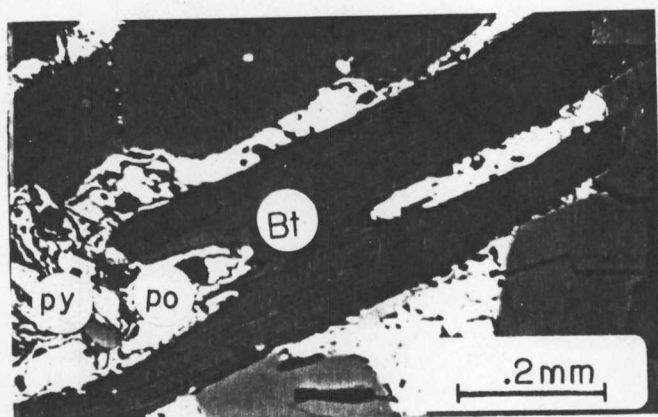
- a. Rounded hornblende island (Hb) in sulfide matrix (po). Specimen D-3A, plane polarized light.
- b. Biotite islands, (dark) randomly oriented in sulfide (light matrix). Note streaks of sulfide in biotite cleavage. Specimen D-3A, reflected light.
- c. Replacement of biotite by sulfides. Specimen D-2, reflected light.
- d. Curved sulfide-hornblende grain boundary. Note sulfide in fractured hornblende. Specimen D-3A, reflected light.
- e. Relict olivine (Ol) island rimmed by discontinuous serpentine. Note serpentine (s) maintains original margin. Specimen D-2, crossed nicols.
- f. Serpentine stringers (dark) in pyrrhotite masses. Specimen D-1, reflected light.



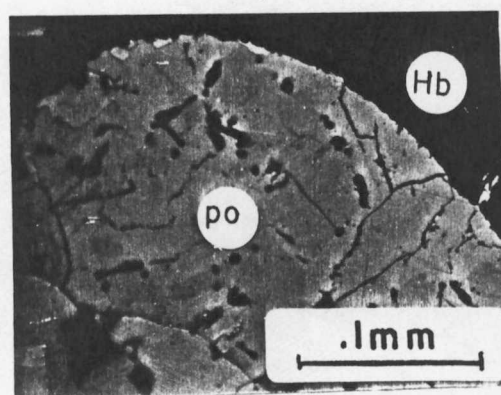
18a



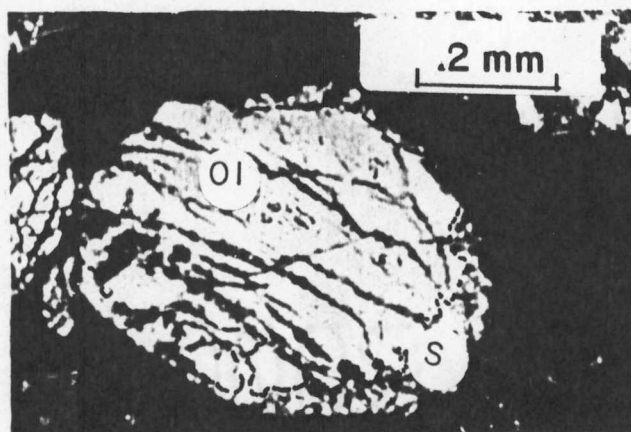
18b



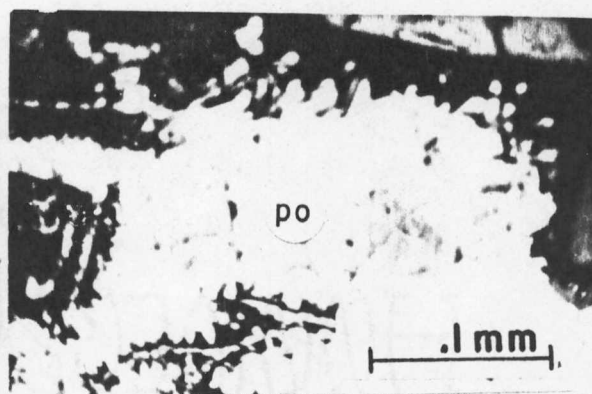
18c



18d



18e



18f

Figure 18.

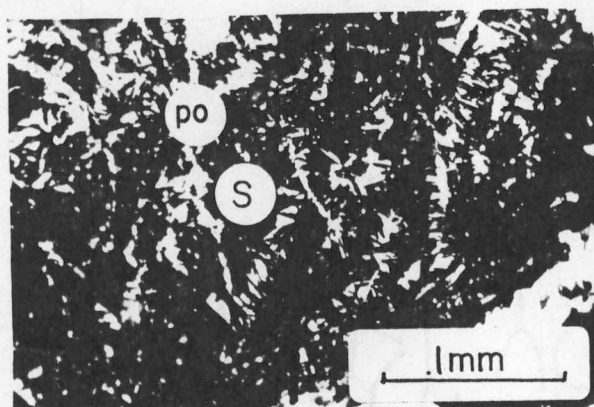
mica or chlorite often penetrate sulfide masses and may even occur as stringers in sulfide masses (Figure 18c).

Occasional olivine pseudomorphs are replaced by serpentine and pyrrhotite (Figure 19a). Grain boundaries between coexisting primary silicates are usually straight, whereas coexisting silicate sulfide grain boundaries are often curved (Figure 19b). Many of the relict olivine grains are also rounded where they are in contact with the sulfides. Annealing textures are rare in the Lick Fork sulfides (Figure 19d), and sulfides often penetrate fractures in silicates (Figure 19c). Pyrrhotite masses are often rimmed by a thin selvage of altered silicates followed by an additional zone of pyrrhotite (Figure 19e). These are termed contraction voids (Taylor, 1970) and are the result of differential cooling of sulfides.

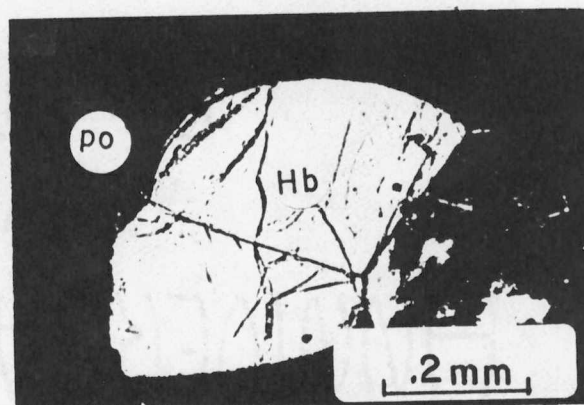
Two discrete sulfide assemblages are present in the hornblende-peridotite unit. These are designated as the pyrrhotite-pentlandite (po-pn) assemblage (Figure 19f), and the pyrrhotite-marcasite-violarite (po-ms-vl) assemblage (Figure 20a). Sulfides in the po-pn assemblage are pyrrhotite, pentlandite, chalcopyrite, violarite, and pyrite. Pyrrhotite is the major sulfide phase which may be partially altered to marcasite. Pentlandite invariably occurs as discrete grains near the margins of the sulfide masses (Figure 20b). Flame texture, common to the pyrrhotite-pentlandite assemblages of the Sudbury ore, is nonexistent in the Lick Fork occurrence. Violarite appears as a minor phase replacing pentlandite along octahedral cleavages and fractures (Figure 19f) as has been described from many other areas (Misra and Fleet, 1974).

Figure 19. Hornblende-peridotite; sulfide-silicate textures.

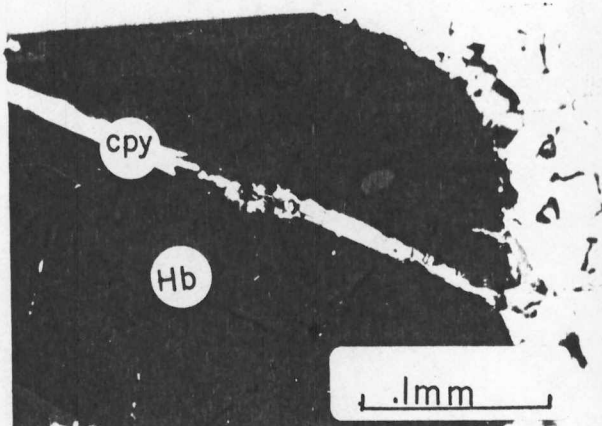
- a. Olivine pseudomorphs replaced by serpentine (s) and pyrrhotite (po). Specimen D-4, reflected light.
- b. Rounded hornblende island (Hb) in sulfide matrix showing straight silicate grain boundaries and triple junction, and curved silicate-sulfide grain boundaries. Specimen D-3A, plane polarized light.
- c. Chalcopyrite (cpy) penetrating fractured hornblende. Specimen D-4, reflected light.
- d. Annealing textures in pyrrhotite. Pyrrhotite-pentlandite assemblage. Specimen D-1, reflected light.
- e. Contraction voids in pyrrhotite. Specimen D-4, reflected light.
- f. Pyrrhotite-pentlandite assemblage, partial violaritization of pentlandite in fractures. Specimen D-3A, reflected light.



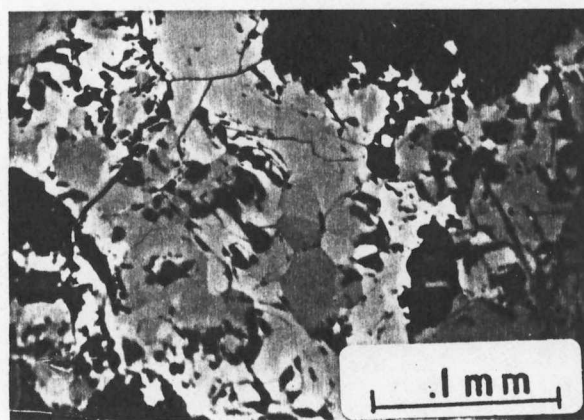
19a



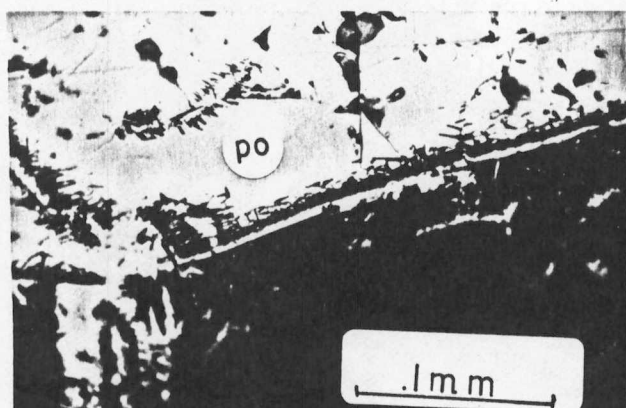
19b



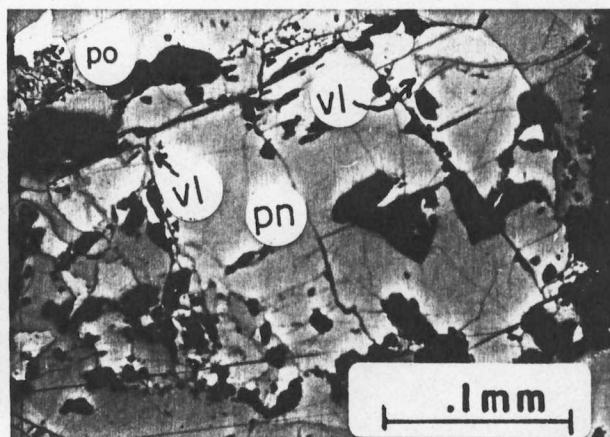
19c



19d



19e

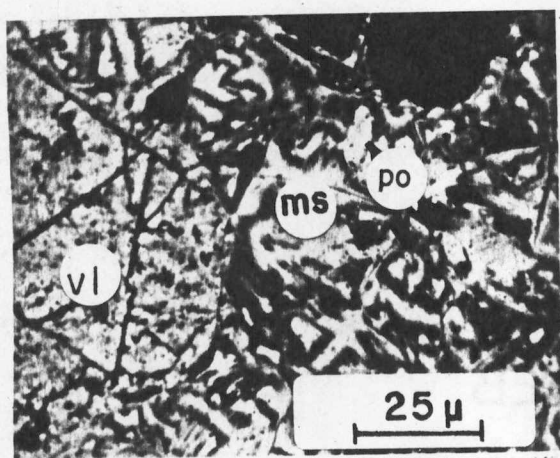


19f

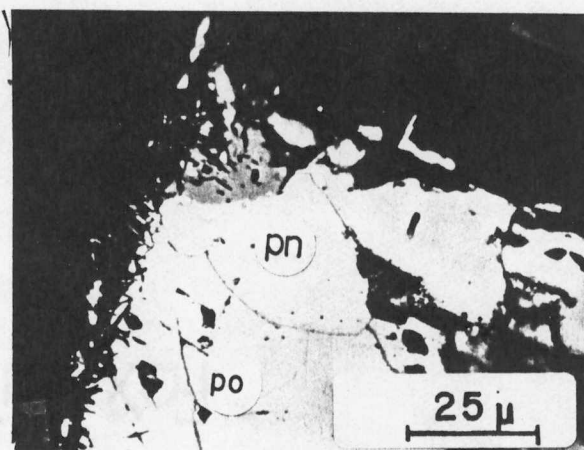
Figure 19.

Figure 20. Sulfide textures; hornblende-peridotite.

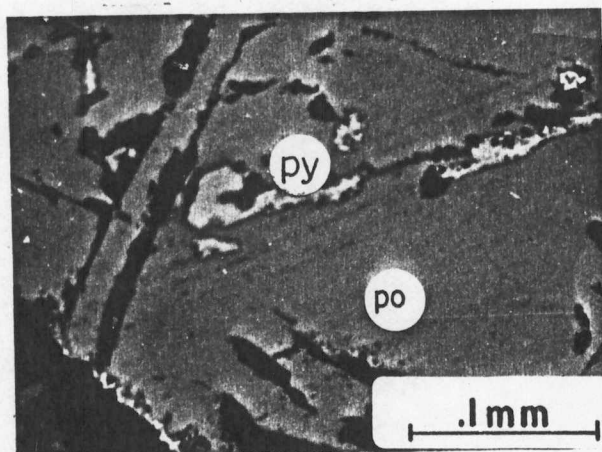
- a. The po-ms-vl assemblage; complete replacement of pentlandite by violarite, and alteration of pyrrhotite to marcasite. Specimen D-4, reflected light.
- b. Pentlandite along pyrrhotite grain margins. Specimen D-3A, reflected light.
- c. Pyrite (py) stringers in pyrrhotite, po-pn assemblage. Specimen D-2, reflected light.
- d. Chalcopyrite (cpy) along pyrrhotite margins, po-pn assemblage. Specimen D-3A, reflected light.



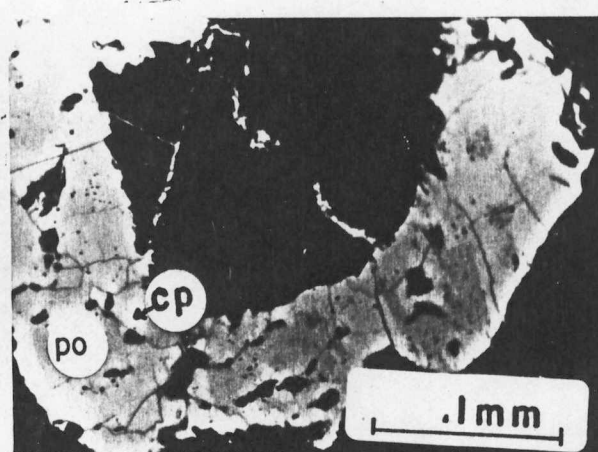
20a



20b



20c



20d

Figure 20.

Violarite has been described as a replacement of pyrrhotite in the nickel ores of the Kambalda District, Australia (Nickel et al., 1974). This feature was not observed in the present study, but an anomalously high Fe-rich violarite in the Lick Fork assemblage was described by Craig and Higgins (1975) as being a replacement of pyrrhotite. The small amount of pyrite in the po-pn assemblage is found as irregular masses and fine veinlets (Figure 20c), the latter often associated with magnetite. Chalcopyrite occurs along grain margins of the pyrrhotite sharing mutual grain boundaries, and as discrete grains in altered silicates (Figure 20d). Chalcopyrite is also in association with magnetite. Other minerals of the po-pn assemblage include occasional mackinawite and bornite.

The po-ms-vl assemblage is characterized by extensive alteration of pyrrhotite to marcasite and replacement of pentlandite by violarite which retains the octahedral cleavage of the original pentlandite (Figure 20a). Pyrite appears as irregular masses associated with pyrrhotite. The po-ms-vl assemblage shows ample evidence of oxidation. The sulfides are often rimmed by goethite, which may also occur in fractures transgressive to the silicate phases. Siderite, a common mineral of oxidation zones, can be found in fractures associated with goethite. In addition, silicates in the po-ms-vl assemblage appear to be more altered than those of the po-pn assemblage.

Annealing and deformation textures are rare in the sulfides of both assemblages, although occasional polygonal aggregates of pyrrhotite are observed (Figure 19d).

Oxide Minerals

The oxide phases common to both the po-ms-v1 and the po-pn assemblages include green spinel (pleonaste), magnetite, ilmenite and rutile.

Pleonaste is xenoblastic and occurs at the margins of sulfide stringers and intergranular to primary silicates; however, it does not share mutual grain boundaries with sulfide grains, nor is it found within the sulfide masses. Pleonaste is commonly present as small blebs within the clinopyroxene but rarely in the hornblende.

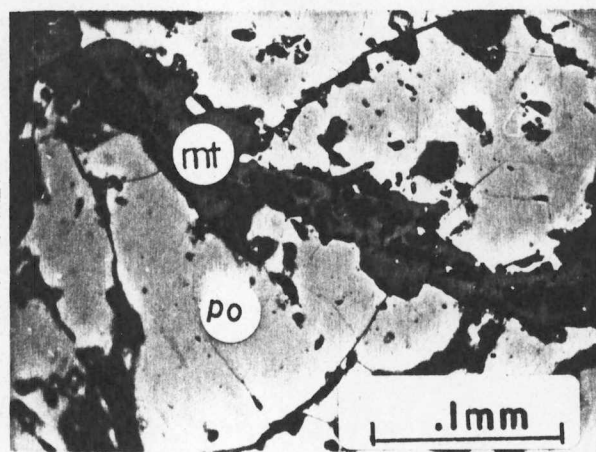
Magnetite is probably the most common phase of the oxides. Texturally, it appears to be secondary in nature, and may be found in the following associations:

- (a) In pyrrhotite, magnetite usually appears as anhedral stringers in fractures within the pyrrhotite and along grain boundaries (Figure 21a).
- (b) Along pleonaste grain boundaries, magnetite occurs as rims and in fractures. Also magnetite occurs as exsolved blebs within the pleonaste (Figure 21b).
- (c) In serpentine, magnetite is abundant as fine disseminations (Figure 21c), clearly a product of serpentinization of olivine.
- (d) Magnetite occasionally forms a complex intergrowth with hornblende which is suggestive of symplectic textures.

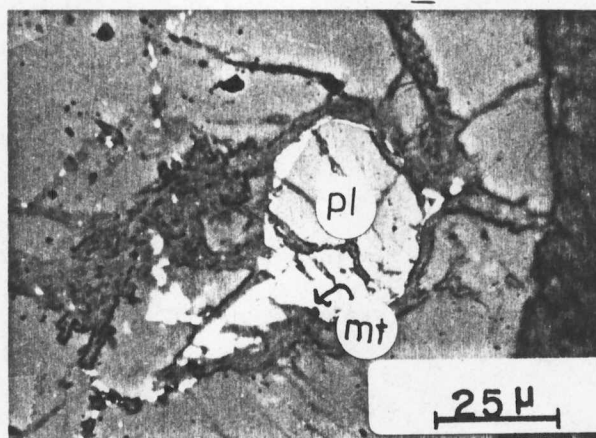
Small lamellae of ilmenite are in the magnetite rims in pleonaste and in disseminated magnetite in serpentine.

Figure 21. Oxide textures in the hornblende-peridotite.

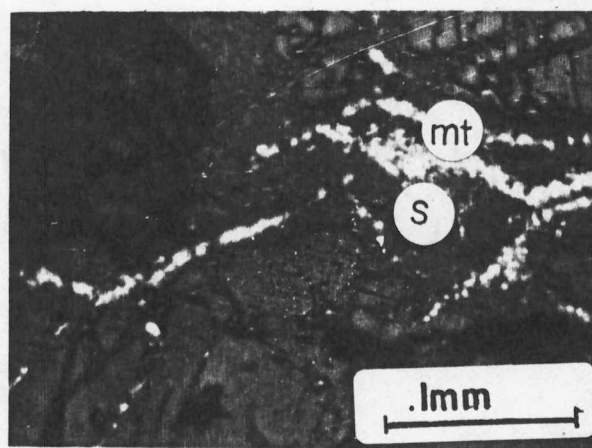
- a. Magnetite stringers in pyrrhotite, po-pn assemblage. Specimen D-1, reflected light.
- b. Magnetite (mt) (light gray) rimming pleonaste. Specimen D-2, reflected light.
- c. Magnetite-serpentine association. Specimen D-1, reflected light.



21a



21b



21c

Figure 21.

Sulfide-Oxide Chemistry

Analyses of sulfides and oxides were confined to the sulfide-rich zone of hornblende-peridotite.

Oxides. Magnetite compositions associated with pyrrhotite, pleonaste and serpentine are presented in Appendix B-9. Compositional variations among the magnetite of different associations are minimal; however, Cr and Ni contents of magnetite associated with the pyrrhotite are significantly lower than Cr and Ni in the other magnetite associations. It is suggested that this magnetite is different in origin than both the magnetite rims and blebs in pleonaste and the disseminated magnetite in the silicates.

Sulfides. Sulfide minerals from the po-pn assemblage analyzed with the electron microprobe include pyrrhotite ($47.5 \pm .5\%$ Fe), pentlandite ($25.6 \pm .6\%$ Fe, $25.1 \pm .4\%$ Ni, and $2.81 \pm .12\%$ Co). Violarite compositions vary from 24-17% Fe to 24-17% Ni and 2.7-3.7% Co (Appendix Table B-8). Average py compositions in the po-ms-vl assemblage are $45.6 \pm .3\%$ Fe, $0.42 \pm .11\%$ Ni, and 0.00% Co. Violarite ranges from 19-21% Fe, 20-22% Ni, and 3-4% Co in the po-ms-vl assemblage.

Pyrrhotite, pentlandite, and pyrite show very little compositional variation, although violarite composition is more variable. This may be attributed to the poor polishing characteristics of violarite in polished thin sections which contribute to difficult quantitative analyses of violarite by electron microprobe techniques (Misra and Fleet, 1974).

No significant variation between violarite of either the po-pn or the po-ms-vl assemblage is observed. When compared to stoichiometric violarite, the Lick Fork violarite appears to be deficient in sulfur. Misra and Fleet (1974) suggest this may be due to the extension of the violarite solid solution field into sulfur deficient compositions.

Fe-Ni content was adjusted for Co by substitution of an amount of Co proportional to the atomic Fe/Ni ratio (Misra and Fleet, 1974). Compositions are presented in the Fe-Ni-S ternary along with other naturally occurring violarite-bearing assemblages (Figure 22). These assemblages of Misra and Fleet (1974) can be broadly classified into three groups based on the appearance of pyrite or pyrrhotite in the assemblage. These are:

1. Assemblages containing pyrite and no pyrrhotite.
2. Assemblages containing both pyrrhotite and pyrite.
3. Assemblages containing pyrrhotite and no pyrite.

From this figure it can be seen that violarite-pentlandite compositions of assemblage 3 (po, no py) are enriched in Ni with respect to pn-vl compositions of assemblage 1 (py, no po). Assemblage 2 compositions (po+py) are intermediate to assemblage 1 and 3. Ni content in violarite and pentlandite decreases with increasing sulfur content of the Fe sulfides, thereby suggesting a possible sulfurization control of pn and vl compositions. The Lick Fork violarite-pentlandite compositions of Figure 22 plot intermediate to the assemblages 1 and 2 of Misra and Fleet (1974). This is in good agreement with the petrographic observation of the Lick Fork assemblages in which both pyrite and pyrrhotite are present.

Lick Fork

- po-pn assemblage ●
- po-ms-vl assemblage ○

Craig & Higgins (1975) ▲

Misra & Fleet, (1974) |

- py-pn-vl-m |

- pσ-pn-vl

- po-pn-py-ms-vl

Nickel & Thornber (1973) ▨

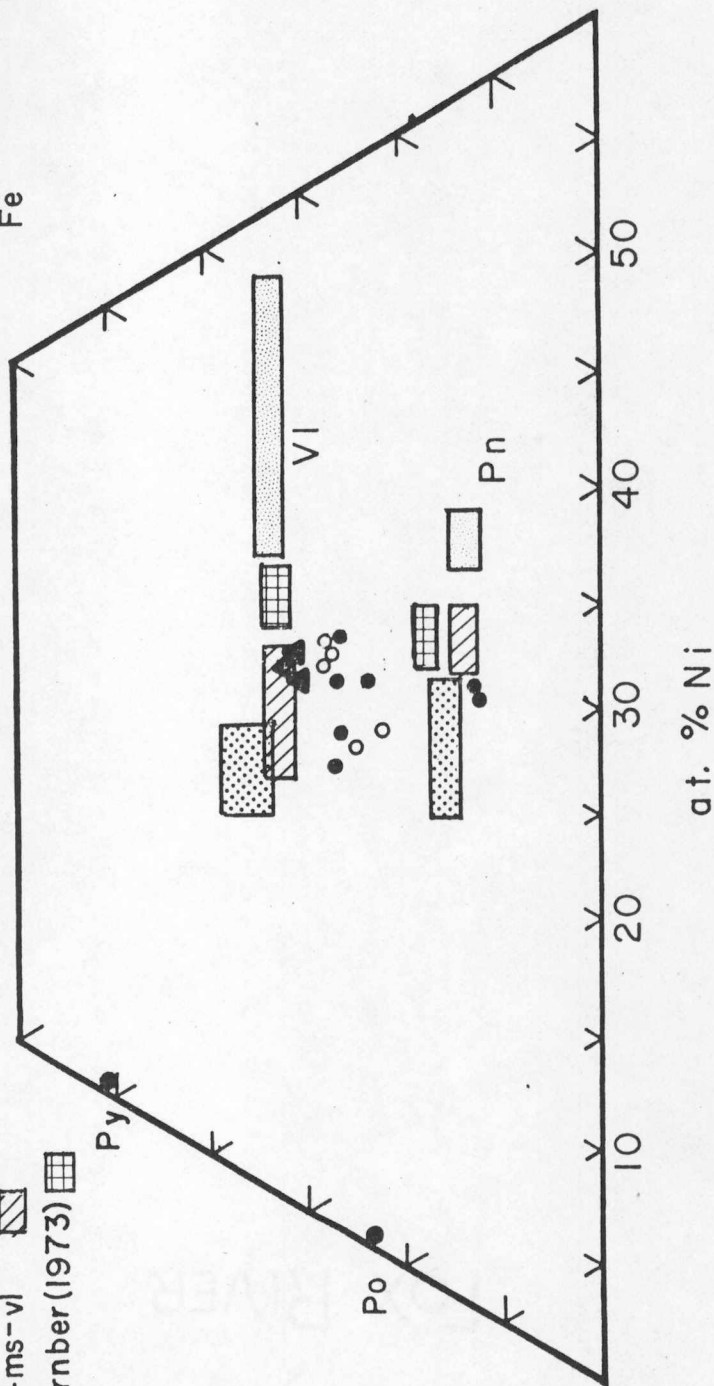
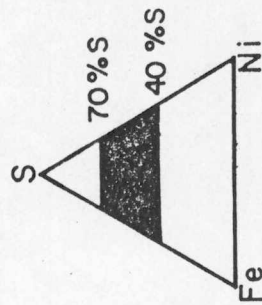


Figure 22. Central portion of the Fe-Ni-S ternary showing compositions of violarite and coexisting phases in the Lick Fork body and other occurrences.

CHAPTER VI

SULFIDE PETROGENESIS

Establishing a primary sulfide origin in metamorphic terrains is limited by the remobilization and rapid equilibration of sulfides under metamorphic conditions (Vokes, 1967; McDonald, 1968). However, comparative observations of petrography and chemistry of the Lick Fork sulfide assemblage to similar occurrences allow for its possible petrogenetic interpretation.

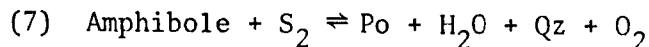
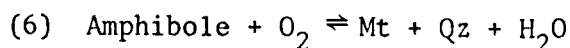
Significance of Sulfide-Silicate Textures

There is considerable evidence of replacement of silicates by sulfides in the Lick Fork body. The rounding of polygonal silicates at sulfide contacts, islands of host rock in the sulfide matrix and corroded silicates in sulfides have been considered as replacement textures (Bell, 1980; Bell and Fleet, 1980; Fleet, pers. comm.). Additional evidence proposed by these workers is the optical continuity of silicate islands in the massive sulfide, which is interpreted as relicts of larger poikiloblastic grains. Olivine pseudomorphs in the hornblende-peridotite are replaced by serpentine and pyrrhotite. Similar replacement textures have been described in the Kambalda Nickel district, Australia (Moeskops and Davis, 1977) and Fennoscandia Nickel deposits (Hapaala, 1969).

Timing of sulfide mineralization. Many of the coexisting primary silicate phases in the hornblende-peridotite have well developed triple

junctions, whereas coexisting sulfide-silicate grain boundaries are usually curved. Straight grain boundaries of the silicates indicate textural equilibrium, where coexisting phases maintain minimum surface free energy (Spry, 1974; Vernon, 1976). Curved grain boundaries, however, indicate textural disequilibrium, such as those seen in the Lick Fork silicate sulfide contacts.

Considerable experimental and theoretical work has been undertaken concerning the effects of f_{O_2} and f_{S_2} on the stability of Fe-Mg in amphibolites (Popp et al., 1977a, 1977b; Froese, 1977). It has been demonstrated by these workers that sulfidation of amphiboles is controlled by f_{O_2} and f_{S_2} for the simultaneous equilibria:



Popp et al. (1977b) determined that amphiboles of 29, 41, 51, 57, mole percent Fe, coexist with pyrrhotites of 0.928, 0.934, 0.943 and 0.950 (Fe at. wt. % $\times 2$) Fe respectively. Fe content of amphiboles in the hornblende-peridotite of the Lick Fork occurrences is 0.220, with coexisting pyrrhotite of 0.950 Fe. According to Froese (1977), amphiboles of 0.22 Fe at 700°C and 1 kb are in equilibrium with pyrrhotite of 0.920 Fe in the presence of magnetite and quartz. The discrepancy between sulfide and hornblende compositions when compared to Froese (1977) and Popp et al. (1977 a,b) implies disequilibrium conditions in the Lick Fork sulfide-silicate assemblages. It must be warned, however, that experimental and theoretical parameters are not entirely correlative with the Lick Fork assemblages, and sulfides re-equilibrate rapidly at lower temperatures and pressures.

Clark and Kelley (1973) demonstrated that pyrrhotite shows the effects of strain in the form of kink banding at pressures of 2 kb. However, both sulfide deformation textures and annealing textures are rare in the Lick Fork sulfides.

Biotite in the sulfide matrix has no preferred orientation with the host rock foliation. Cross-cutting relationships of silicates by the sulfides indicate an epigenetic origin of the sulfides.

The texture and chemistry of the Lick Fork sulfides and silicates indicate disequilibrium with granulite facies metamorphism. The transgressive relationships and the absence of a strong metamorphic fabric of the sulfides argue for a post-granulite origin of the sulfides. The encroachment of euhedral chlorite and sericite into the pyrrhotite margins and serpentine inclusions in the sulfide matrix indicates that sulfides were emplaced after alteration of the primary silicates. Post serpentinization emplacement of the sulfides explains the discontinuous serpentine selvage which is in contact with olivine and sulfides.

Discussion

At present, there is considerable debate over the primary origin of Ni-sulfide deposits of ultramafic and mafic rocks. Naldrett and Cabri (1976) and Naldrett (1973,1980) argue for a magmatic origin of Ni-sulfides from an immiscible sulfide melt. The primary arguments propounded by Naldrett (1980) for magmatic immiscibility are:

1. The invariable occurrence of sulfides at the stratigraphic base of the unit with which they are associated.

2. The interstitial nature of the sulfides to the silicates (net texture) whereby Naldrett's billiard ball model is employed to explain the occurrence of euhedral cumulate olivine in the sulfide matrix.

Fleet (1977,1979) and Fleet et al. (1977) suggest a hydrothermal origin of Ni- sulfides in the Sudbury Irruptive, using as their arguments:

1. The variable composition of pyrrhotite is incompatible with immiscibility.
2. Partitioning of Ni between olivine and sulfide in most orebodies is incompatible with experimental data.
3. Texturally, sulfides are replacing metamorphic amphiboles and chlorite.

Naldrett (1969) concedes that not all net textured ore may be magmatic in origin, and cites evidence for replacement in several Ni deposits throughout the world.

It is generally accepted that magmatic sulfides co-precipitate with oxides from an immiscible sulfide-oxide melt (Naldrett, 1969; Haughton et al., 1974). There is no textural evidence of an early cumulate or relict cumulate magnetite phase in the Lick Fork ultramafic unit. The low Cr_2O_3 content of the magnetite stringers in pyrrhotite (0.13% Cr_2O_3 ; see Appendix Table B-9), when compared to magmatic magnetite compositions of Sudbury (2-6% Cr_2O_3 ; Naldrett and Gasparrini, 1972), and the absence of magmatic textures, indicate the oxides in the hornblende-peridotite did not crystallize from an immiscible sulfide melt.

It has been argued above that sulfide mineralization in the Lick Fork body is replacement in origin, and post-metamorphic in age. The absence of metamorphic sulfide textures and primary magmatic oxides preclude the existence of a pre-metamorphic (magmatic) sulfide. The rounding of polygonal silicates at sulfide contacts, corroded islands of host rock in the sulfide matrix, and the optical continuity of silicate islands in the sulfide matrix, have been interpreted by Bell (1980) and Bell and Fleet (1980) as evidence for hydrothermal replacement. Olivine pseudomorphs replaced by serpentine and pyrrhotite, and the discontinuous serpentine selvage around olivine grains have been argued for post-serpentinization mineralization by hydrothermal fluids (Moeskops and Davis, 1977; Hapaala, 1969).

Sulfide mineralization in the Lick Fork body is therefore interpreted as being hydrothermal in origin. Although the source of the sulfur is uncertain, Fe and Ni cations may have been scavenged from the replaced mafic silicates in the ultramafic unit. Mineralizing fluids probably migrated along fractures in the hornblende-peridotite which were formed by earlier faulting at the hanging wall contact.

The association of sulfides with the foliated aggregates of anhydrous mafic phases and the absence of sulfides from the coarse-grained hornblende aggregates are indicative of the selective processes of hydrothermal replacement. Similar features of selective replacement by sulfides have been described in the Ni ores of the Ungava District, Quebec (Philpotts, 1961), where sulfides have selectively replaced pyroxene, olivine, and serpentine and have not replaced metamorphic

amphiboles. This preferential replacement of anhydrous mafic silicates along fractures may account for the foliated net textured mineralization in the Lick Fork body.

Sulfide alteration. Nickel et al. (1974), Blain and Andrews (1977) and Woodall and Travis (1969) discuss three zones in the alteration profile of the Kambalda nickel deposits. The uppermost zone is an oxide zone, which is characterized by the decomposition of sulfide minerals and the development of ferric oxides, gaspeite and nickel magnesite (Nickel, 1974). This zone overlies a violarite-pyrite zone which is typified by the complete replacement of primary pentlandite by violarite, and pyrrhotite by secondary pyrite and marcasite. The po-ms-v1 assemblage of the Lick Fork sulfides is equivalent mineralogically to this zone although, in this case, pyrrhotite is not completely replaced. The transition zone is the zone between the primary unaltered ore and the violarite-pyrite zone. Nickel et al. (1974) describe this as the zone of incipient violaritization of pentlandite. This is probably equivalent to the po-pn assemblage of the Lick Fork occurrence.

Violarites in the violarite-pyrite zone in the Kambalda district become progressively enriched in Ni with increasing depth (Nickel et al., 1974). These workers attribute the Ni enrichment of violarite in the Ni-rich fluids descending from the oxide zone, and predict that after oxidation of pyrrhotite to secondary pyrite in the oxidation zone occurs, the increasing Eh will increase Ni activity resulting in the consequent enrichment of Ni in violarite.

Comparison of this observation with Misra and Fleet's (1974) data of Canadian nickel deposits show that violarite (and pentlandite) have more Ni-rich compositions in the pyrite-bearing assemblages. Misra and Fleet (1974), however, warn that the Kambalda weathering is considerably different than that of the Canadian Ni deposits, and that caution should be observed in comparing the petrogenesis of the two.

Violarite compositions for the Lick Fork po-ms-vl assemblages do not show a Ni enrichment as discussed by Nickel et al. (1974). This may reflect either a difference in the weathering environment, or may be a function of depth since the gossan zone in the Lick Fork body appears to be superficial.

Craig and Higgins (1975) discuss the origin of violarite in the Lick Fork body as either representing the adjustments in a supergene environment, or as being products of hydrothermal alteration. As discussed earlier, the assemblage is associated with Fe-carbonates and oxides such as goethite. This feature, in addition to the occurrence of gossan over much of the surface of the ore zone suggests that supergene enrichment may have played a more active role in the violaritization of pentlandite than hydrothermal processes.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The sequence of events concerning the evolution of the Lick Fork body is as follows:

1. Multiple intrusions of differentiated magmatic fluid into country rock. Cross-cutting relationships and comparison of mafic assemblage to the country rock indicate the Lick Fork body is magmatic in origin. Systematic variation in composition and mineralogy, suggest magmatic differentiation. Spatial relationships of the gabbroic and ultramafic lithologies imply magmatic intrusions.
2. Prograde (?) metamorphism to hornblende-granulite facies and equilibration of silicate phases. Compositions of pyroxene and hornblende, and partitioning of Fe-Mg in coexisting silicates suggest granulite-facies metamorphism at $P \leq 5$ kb and $T = 600-700^{\circ}\text{C}$. Comparison of composition and mineralogy to those produced by theoretical metamorphism suggest prograde metamorphism. Hornblende stability is dependent upon Mg/Fe content of amphibole.
3. Introduction of volatiles at peak metamorphism causing clinopyroxene-hornblende reactions.
4. Faulting of the intrusion at the hanging wall contact imparting a tectonic overprint upon the Lick Fork body, providing conduits for later mineralizing fluids.
5. Alteration of primary silicates to sericite, chlorite and serpentine by selective migration of hydrothermal fluids.

6. Sulfide replacement of silicates by hydrothermal processes.
7. Oxidation of primary sulfides and pleonaste, giving magnetite rims on spinel and magnetite stringers in sulfides.
8. Surface oxidation and supergene enrichment of sulfides.

From this research, it has been shown that the Lick Fork ultramafic-mafic host rocks are metamorphic in origin rather than a primary magmatic origin as described by Watson (1907), Ross (1935) and Craig and Higgins (1975). Because of the problems associated with charnockites, the actual mechanism of formation is only speculative at best. Sulfide mineralization is the result of hydrothermal and supergene processes rather than magmatic processes as is often assumed for Ni deposits of this association.

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APPENDICES

APPENDIX A

SAMPLING AND STUDY METHODS

APPENDIX A

SAMPLING AND STUDY METHODS

I. Mapping

An area of about 9km^2 of the country rock was mapped in order to obtain a coherent picture of the regional geologic setting. In addition, detailed mapping of the Lick Fork body was carried out in order to establish structural relationships of the Lick Fork lithologic units.

II. Sampling

Since the lithologies within the host rock change normal to its strike, selective sampling was carried out at about 1.5m intervals on a traverse across the apparent strike of the intrusion and into the country rock. Severe weathering in some of the in situ samples required that specimens be collected at random from the mine dump. The samples collected in situ were consecutively numbered according to their location along the traverse. The numbering of the random samples from the mine dump are preceded by the letter "D." A complete list of the samples studied for this project is given in Appendix C.

III. Sample Preparation and Analysis

Polished thin sections of the samples were made, and textures and mineralogy were studied under the petrographic microscope. Modal

analyses of the silicate phases using the point-count method of Van der Plas and Tobi (1965) were made of the thin sections of samples collected across the strike of the intrusion.

Compositional data for silicate, sulfide, and oxide phases were obtained utilizing an automated MAC 400-S electron microprobe with natural and synthetic standards. An excitation potential of 15KV and a beam current of .030-.050 was employed with a beam diameter of 1-2 μ . Correction for matrix effects were applied according to the procedures described by Bence and Albee (1968), Albee and Ray (1970), and Ziebold and Ogilvie (1964).

Several points on a traverse across each grain were probed in order to observe possible zonation within a grain. Within a given sample, several grains of each phase were analyzed to compare compositions between individual grains. As in the case of modal analysis, the samples subjected to chemical analysis represent a traverse across strike of the Lick Fork body.

IV. Classification Scheme

Because of the controversial nature of origin, a genetic classification of the Lick Fork lithologies is problematical. The classification scheme of granulites according to Winkler (1976) is defined by mineral assemblages, and if necessary, by supplemental textural terminology. His classification system, however, does not include rocks of the "igneous-looking" charnockite suite, although the mineralogy is analogous. Rocks of ultramafic composition are also excluded from this classification system.

The classification of Tobi (1971) for charnockites is based on the system of Streckheisen (1967) for igneous rocks. Again, this system does not include rocks of ultramafic composition.

Bhattacharyya (1974) suggested the use of a non-genetic system of charnockite nomenclature, similar to that of Winkler and Sen (1973). As in the systems discussed above, ultramafic lithologies are excluded. Attempts were made by this worker to classify the Lick Fork lithologies on a basis of modal content of silicate phases, according to the system of Streckheisen (1967). However, this nomenclature proved to be unwieldy for descriptive purposes. The following classification for the Lick Fork mafic-ultramafic lithologies has been followed for the purpose of the present report:

1. Rocks of ultramafic composition are designated as hornblende-peridotite, on the basis of the major mafic phases present.
2. Rocks of ultramafic composition are designated as gabbro or, if hornblende is present, hornblende-gabbro.
3. The felsic, pyroxene-bearing country rock is an alkali-pyroxene syenite, using the system of Tobi (1971) for charnockites.

As has been discussed in the text, the country rocks as well as the rocks of the Lick Fork body have been metamorphosed. The prefix meta-, although appropriate, has been omitted for simplicity.

V. Al^{iv}-Al^{vi} Calculations

To calculate the value of Al^{iv} for a mafic silicate phase from the total Al obtained by electron microprobe analysis, it was assumed

that the tetrahedral coordination position (Z) in its structural formula is completely accounted for by Si^{4+} and Al^{3+} ions. Thus, the value of Al^{iv} was determined from the relation:

$$(A1) \quad Z_{\text{total}} = \text{Si} + \text{Al}^{\text{iv}}$$

For pyroxenes (4 cations on a 6 oxygen basis), $Z = 2$; for hornblendes (16 cations on a 23 oxygen basis), $Z = 8$.

The value of Al^{vi} , then was given by:

$$(A2) \quad \text{Al}_{\text{total}} = \text{Al}^{\text{iv}} + \text{Al}^{\text{vi}} .$$

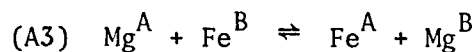
VI. Fe^{2+} - Fe^{3+} Calculations

From the total Fe obtained by electron microprobe analysis of a given mafic phase (orthopyroxene, clinopyroxene, hornblende, biotite), the Fe^{2+} - Fe^{3+} values were calculated by using a charge-balance method, assuming that the Al^{iv} - Al^{vi} distribution as discussed above (equations A1 and A2) is valid.

However, in the present study, the reliability of the calculated Fe^{2+} - Fe^{3+} would be limited by the fact that the mafic phases were not analyzed for elements such as Na, Mn and Cr. Recasting of the electron microprobe analyses showed that the proportion of Fe^{3+} relative to Fe^{2+} is very small to negligible in most cases. Thus the errors in Fe^{3+} calculations have negligible effects on the various plots (e.g., Figures 11, 12, 13, and 16, pages 34, 37, 38, 48) which make use of Mg/Fe^{2+} ratios. On the other hand, small errors in Fe^{3+} values would produce large errors in the $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratios; therefore, $\text{Fe}^{2+}/\text{Fe}^{3+}$ have not been used in the present study.

VII. Mg-Fe Distribution Coefficients

Consider an exchange reaction between Mg and Fe^{2+} in two coexisting phases A and B in equilibrium:



Assuming ideal mixing (so that activity coefficients are equal to unity), the distribution coefficient (K_d) is defined by the equation (Kretz, 1961, 1963; Ray and Sen, 1970):

$$(A4) \quad K_{d(\text{Mg-Fe}^{2+})}^{A-B} = x_{\text{Mg}}^A / (1 - x_{\text{Mg}}^A) \cdot (1 - x_{\text{Mg}}^B) / x_{\text{Mg}}^B$$

where X equals molar concentration expressed as $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$. Equation (A4) may be rearranged as:

$$(A5) \quad K_{d(\text{Mg-Fe}^{2+})}^{A-B} = (\text{Mg}/\text{Fe}^{2+})^A / (\text{Mg}/\text{Fe}^{2+})^B$$

If the mixing is ideal, a plot of $(\text{Mg}/\text{Fe}^{2+})^A$ vs. $(\text{Mg}/\text{Fe}^{2+})^B$ should produce a straight line through the origin, the slope of the line defining the value of K_d . According to Hermes (1970), departure from a straight line plot may be caused by (1) a departure from ideality as a result of compositional variation; (2) attainment of solid solution limits; (3) departure from equilibrium; and/or (4) different temperatures and pressures of equilibration.

Average $K_{d(\text{Mg-Fe}^{2+})}$ values for coexisting Lick Fork silicates are summarized in Table A-1.

TABLE A-1
 AVERAGE $K_d(\text{Mg-Fe}^{2+})$ VALUES FOR COEXISTING SILICATES
 IN THE LICK FORK BODY

Sample	$K_d(\text{Mg-Fe}^{2+})$			
	Opx-Cpx	Opx-Hb	Cpx-Hb	Opx-Bt
D-1	.582	1.044	1.747	.689
809	.602	---	---	---
810A	.537	---	---	1.442
811	.504	.861	1.724	1.576
814	.558	.903	1.495	.887
816	.579	.820	1.411	---

APPENDIX B

MODAL AND ELECTRON MICROPROBE ANALYSES

TABLE B-1

MODAL ANALYSES (VOLUME %) OF THE LICK FORK LITHOLOGIES

Sample No.	D-3	809	910	810A	811	812	813	814	815	816	817
No. of Pts.	1282	614	1350	795	1163	1235	1059	1283	1377	1384	1105
Ol	18.0	13.0	---	---	---	---	---	---	---	---	---
Opx	16.0	19.0	31.0	22.9	41.0	34.7	34.0	39.0	41.0	31.0	40.0
Cpx	5.5	.6	12.0	20.4	18.0	20.0	13.0	25.0	22.0	22.0	14.0
Plag	---	---	55.0	52.8	27.0	33.8	29.0	24.0	27.0	29.0	20.0
Hb	33.0	32.0	---	---	6.3	7.2	12.0	3.0	2.0	7.0	11.0
Bt	2.0	3.0	tr	1.0	8.0	4.3	12.0	9.0	8.0	11.0	15.0
Sulfide	23.0	30.0	tr	tr	tr	tr	tr	tr	tr	tr	tr
Pleonaste	2.5	2.4	---	---	---	---	---	---	---	---	---
mt	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
ilm	tr	tr	2.0	2.9	tr	tr	tr	tr	tr	tr	tr
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Recalculated to 100% Silicates											
Ol	24.1	19.5									
Opx	21.4	27.9									
Cpx	7.3	1.0									
Hb	44.2	47.1									
Bt	3.0	4.6									
Total	100.0	100.0									

TABLE B-2
REPRESENTATIVE ELECTRON MICROPROBE ANALYSES OF
CLINOPYROXENES (WT.%)

		Sample Number				
D-1(6)*		809(4)	810A(6)	811(4)	814(6)	816(7)
SiO ₂	52.8(5)**	50.2(6)	52.4(4)	50.6(4)	52.3(4)	51.8(7)
TiO ₂	0.16(1)	0.36(1)	0.37(4)	0.40(1)	0.47(1)	0.31(2)
Al ₂ O ₃	2.50(2)	3.71(12)	2.64(28)	3.33(5)	2.97(5)	2.81(6)
FeO	5.09(19)	5.39(4)	9.48(28)	6.98(16)	6.47(26)	6.88(56)
MgO	15.6(3)	15.8(4)	14.1(2)	14.7(3)	15.1(4)	15.8(5)
CaO	21.9(1)	22.6(7)	22.1(4)	21.7(2)	22.0(4)	22.2(5)
Na ₂ O	na	na	na	0.55(1)	na	na
Total	98.05	97.97	101.09	98.38	99.36	99.88
Cations Based on 6 Oxygen						
Si	1.965	1.885	1.936	1.902	1.936	1.919
Al	.107	.162	.110	.144	.128	.120
Ti	.004	.009	.008	.011	.013	.008
Fe	.156	.165	.290	.219	.200	.211
Mg	.866	.884	.775	.824	.832	.874
Ca	.873	.909	.876	.876	.872	.878
Na	---	---	.062	---	---	---
Total	3.971	4.014	3.994	4.038	3.981	4.010
En	46.02	45.66	40.23	43.30	43.97	44.66
Fs	7.59	7.38	14.33	10.66	9.95	10.48
Wo	46.38	46.96	45.43	46.04	46.08	44.86
Mg/ (Mg+Fe)	.858	.860	.737	.802	.815	.810

*Units in () represents number of analyses averaged.

**Units in () represent one standard deviation of replicate analysis in terms of least units cited.

na—not analyzed.

TABLE B-3
 REPRESENTATIVE ELECTRON MICROPROBE ANALYSES OF
 ORTHOPYROXENES (WT.%)

	Sample Number						
	D-1(6)*	809(6)	810A(6)	810B(5)	811(6)	914(6)	816(6)
SiO ₂	54.3(4)**	52.6(7)	51.4(5)	51.0(4)	52.0(3)	53.7(8)	52.9(6)
Al ₂ O ₃	2.31(7)	2.91(18)	1.41(3)	1.34(1)	1.88(4)	1.67(16)	1.91(11)
TiO ₂	0.05(1)	0.09(1)	0.18(1)	0.05(1)	0.03(2)	0.19(7)	0.08(1)
FeO	14.0(5)	14.8(7)	24.5(2)	22.8(4)	19.6(2)	17.7(3)	18.0(1)
MgO	29.1(4)	28.9(2)	20.1(2)	22.3(1)	24.9(1)	25.9(5)	26.4(3)
CaO	0.60(5)	0.52(7)	0.64(1)	0.57(2)	0.50(4)	0.51(9)	0.47(3)
Total	100.4	99.82	98.23	98.06	98.91	99.67	99.86
Cations Based on 6 Oxygen							
Si	1.935	1.897	1.970	1.943	1.939	1.958	1.934
Al	.094	.121	.059	.059	.080	.070	.078
Ti	.002	.002	.005	.002	.002	.004	.002
Fe	.417	.444	.783	.726	.616	.539	.551
Mg	1.545	1.552	1.147	1.267	1.375	1.407	1.437
Ca	.021	.021	.025	.022	.017	.019	.017
Total	4.014	4.037	3.989	4.019	4.019	3.997	4.019
En	78.06	77.80	59.06	63.47	69.09	72.04	72.10
Fs	20.86	21.07	39.64	35.42	30.05	26.91	27.04
Wo	1.08	1.13	1.30	1.11	.86	1.05	.86
Mg/ (Mg+Fe)	.789	.787	.598	.641	.696	.727	.712

*Units in () represent number of analyses averaged.

**Units in () represent one standard deviation of replicate analysis in terms of least units cited.

TABLE B-4
REPRESENTATIVE ELECTRON MICROPROBE ANALYSES OF
BIOTITE (WT.%)

	Sample Number			
	D-1(4)*	810A(6)	811(6)	814(4)
SiO ₂	35.6(1)**	35.3(12)	34.5(8)	36.8(4)
Al ₂ O ₃	16.7(2)	15.2(6)	15.3(8)	14.7(1)
TiO ₂	2.37(5)	2.87(10)	4.41(11)	4.98(12)
FeO	7.16(29)	18.8(4)	17.3(9)	10.6(2)
MgO	21.1(1)	11.0(6)	14.7(4)	17.1(6)
MnO	0.10(7)	0.14(7)	0.14(2)	0.09(2)
CaO	0.02(4)	0.08(2)	0.09(2)	0.03(2)
Na ₂ O	0.17(4)	0.29(4)	0.24(3)	0.18(4)
K ₂ O	9.44(8)	8.57(33)	8.79(9)	9.64(25)
Total	92.66	92.71	98.38	94.13
<u>Cations Based on 11 Oxygen</u>				
Si	2.651	2.624	2.619	2.740
Al	1.460	1.332	1.368	1.289
Ti	.129	.156	.251	.277
Fe	.443	1.166	1.095	.658
Mg	2.341	1.216	1.661	1.898
Mn	.004	.004	.004	.000
Ca	.000	.004	.004	.000
Na	.018	.034	.026	.016
K	.894	.804	.848	.912
Total	7.940	7.340	7.876	7.790
Mg/ (Mg+Fe)	.840	.510	.602	.742

*Units in () represent number of analyses averaged.

**Units in () represent one standard deviation of replicate analysis in terms of least units cited.

TABLE B-5
REPRESENTATIVE ELECTRON MICROPROBE ANALYSES OF
HORNBLLENDE (WT.%)

	Sample Number				
	D-1 ¹ (6)*	D-1 ² (5)	811(6)	814(5)	816(6)
SiO ₂	42.5(5)**	41.8(3)	41.0(5)	41.4(8)	42.1(2)
Al ₂ O ₃	13.2(4)	13.6(2)	12.4(1)	12.3(1)	11.9(1)
TiO ₂	1.15(5)	1.28(2)	2.86(2)	2.75(13)	2.05(5)
FeO	7.83(30)	7.85(37)	9.51(7)	9.09(37)	8.75(17)
CaO	12.2(5)	11.7(1)	11.8(1)	12.0(1)	11.6(1)
MgO	15.5(2)	15.7(3)	13.7(1)	13.9(4)	14.8(1)
Na ₂ O	2.35(13)	2.26(6)	2.10(1)	1.88(12)	2.02(6)
K ₂ O	1.06(14)	1.25(3)	1.67(1)	1.57(2)	1.42(4)
Total	95.86	95.46	95.04	94.89	94.69
<u>Cations Based on 23 Oxygen</u>					
Si	6.274	6.204	6.204	6.247	6.338
Al	2.292	2.374	2.201	2.178	2.100
Ti	.124	.142	.318	.308	.226
Fe	.959	.973	1.2-0	1.144	1.095
Mg	3.430	3.472	3.094	3.123	3.323
Ca	1.937	1.857	1.910	1.934	1.814
Na	.674	.642	.600	.544	.578
K	.194	.232	.308	.290	.276
Total	15.884	15.896	15.825	15.768	15.746
Mg/ (Mg+Fe)	.776	.781	.719	.731	.752

¹"Primary" Hb.

²"Secondary" Hb, reaction product of augite.

*Units in () represent number of analyses averaged.

**Units in () represent one standard deviation of replicate analysis in terms of least units cited.

TABLE B-6
 REPRESENTATIVE ELECTRON MICROPROBE ANALYSES OF
 PLAGIOCLASE (WT.%)

	Sample Number			
	810A(6)*	811(6)	812(6)	817(6)
SiO ₂	56.9(2)**	52.1(7)	52.8(6)	52.9(5)
Al ₂ O ₃	27.1(2)	30.4(4)	29.7(4)	29.7(5)
Na ₂ O	6.50(26)	4.29(18)	5.04(8)	4.80(12)
CaO	9.18(11)	12.4(6)	11.6(1)	11.7(2)
K ₂ O	<u>0.22(7)</u>	<u>0.08(3)</u>	<u>0.09(4)</u>	<u>0.08(1)</u>
Total	99.9	99.3	99.2	99.1
<u>Cations Based on 8 Oxygen</u>				
Si	2.559	2.437	2.407	2.411
Al	1.434	1.675	1.595	1.594
Na	.562	.386	.444	.420
Ca	.441	.621	.564	.569
K	<u>.010</u>	<u>.004</u>	<u>.004</u>	<u>.004</u>
Total	5.006	5.123	5.014	4.998
An	43.6	61.3	55.7	56.8
Ab	55.5	38.0	43.8	42.8
Or	0.9	0.3	0.5	0.4

*Units in () represent number of analyses averaged.

**Units in () represent one standard deviation of replicate analysis in terms of least units cited.

TABLE B-7
 REPRESENTATIVE ELECTRON MICROPROBE ANALYSES OF
 OLIVINE (WT.%) ULTRAMAFIC ZONE

Sample No. D-1(5)*	
FeO	21.1(12)**
MgO	41.4(.7)
SiO ₂	<u>38.2(.3)</u>
Total	100.7
<u>Cations Based on 4 Oxygen</u>	
Fe	.446
Mg	1.599
Si	<u>.977</u>
Total	3.022

*Units in () represent number of analyses averaged.

**Units in () represent one standard deviation of replicate analyses in terms of least units cited.

TABLE B-8
 REPRESENTATIVE ELECTRON MICROPROBE ANALYSES OF
 SULFIDE MINERALS, ULTRAMAFIC ZONE (WT.%)

	Sample D-1				
	Po(5)*	Pn(5)	Py(3)	v1 ¹ (5)	v1 ² (5)
Fe	61.6(3)**	31.6(1)	45.6(3)	26.6(19)	23.7(12)
Ni	0.40(5)	32.6(1)	0.42(11)	28.4(23)	26.1(10)
Co	0.04(3)	3.71(14)	0.00	3.77(20)	3.91(27)
S	<u>38.8(5)</u>	<u>32.7(2)</u>	<u>50.1(2)</u>	<u>37.9(10)</u>	<u>36.9(1)</u>
Total	100.84	100.0	96.25	96.67	90.6
Atomic Percent					
Fe	47.5	25.6	34.1	21.6	20.3
Ni	0.25	25.1	.29	21.9	21.3
Co	0.03	2.81	0.00	2.85	3.16
S	<u>52.2</u>	<u>46.2</u>	<u>65.5</u>	<u>53.6</u>	<u>55.1</u>
Total	99.9	99.9	100.0	99.9	99.9

*Units in () represent number of analyses averaged.

**Units in () represent one standard deviation of replicate analysis in terms of least units cited.

¹ po-pn assemblage.

² ms-v1 assemblage.

TABLE B-9
 REPRESENTATIVE ELECTRON MICROPROBE ANALYSES FOR
 OXIDES (WT.%) FROM THE ULTRAMAFIC ZONE

	Pleonaste	Mt ¹	Mt ²	Mt ³	Ilmenite
FeO	23.49	30.46	30.34	30.55	34.23
MgO	10.16	.30	.18	.23	1.66
MnO	.54	.25	nd	.34	8.95
NiO	.09	.19	.05	.19	.20
Al ₂ O ₃	47.43	1.92	.13	.25	.41
Cr ₂ O ₃	11.21	2.21	.13	3.86	.13
TiO ₂	.02	.20	.16	.32	50.86
Fe ₂ O ₃	<u>7.15</u>	<u>61.84</u>	<u>65.48</u>	<u>62.91</u>	<u>2.86</u>
Total	100.09	97.34	96.47	98.65	99.30
<u>Cations Based on 4 Oxygens</u>					
Fe ²⁺	.558	.994	1.011	.992	.718
Mg	.431	.017	.011	.013	.062
Mn	.130	.008	---	.011	.190
Ni	.002	.006	.002	.006	.004
Al	1.590	.088	.006	.011	.012
Cr	.252	.068	.004	.118	.002
Ti	<u>0.000</u>	<u>.005</u>	<u>.004</u>	<u>.009</u>	<u>.960</u>
Total	3.116	5.004	2.996	3.002	2.003

¹Magnetite rims in pleonaste.

²Magnetite rimming pyrrhotite.

³Magnetite disseminations in serpentine.

APPENDIX C

PETROGRAPHY OF LICK FORK LITHOLOGIES

TABLE C-1
MINERAL ABBREVIATIONS

An	Anorthite	ms	Marcasite
bn	Bornite	mk	Mackinawite
Bt	Biotite	Ol	Olivine
Cpx	Clinopyroxene	Opx	Orthopyroxene
cpy	Chalcopyrite	Plag	Plagioclase
En	Enstatite	po	Pyrrhotite
Ed	Edenite	pn	Pentlandite
Fs	Ferrosilite	py	Pyrite
Ha	Hastingsite	Qtz	Quartz
Hb	Hornblende	sp	Spinel (pleonaste)
ht	Hematite	Ts	Tschermakite
ilm	Ilmenite	Wo	Wollastonite
mt	Magnetite	vl	Violarite

TABLE C-2
 PETROGRAPHIC DESCRIPTIONS OF LICK FORK COUNTRY ROCK;
 HAND SPECIMENS

Sample Number	Lithology and Description
101 105 110	<u>Biotite-gneiss</u> —Mafic gneiss highly foliated interlayered quartz, feldspar and mafic phases of biotite and amphibole. Tr. cpy. Specimen #110 is coarse felspar and quartz augen in biotite gneiss.
106 114 116 117	<u>Muscovite-granitic gneiss</u> —Coarse-grained orthoclase and quartz with foliated muscovite.
126 128 129 131 132 135	127 130 <u>Alkali-pyroxene syenite</u> —Medium- to coarse-grained feldspar and quartz with bands of altered orthopyroxene. Scattered garnet specimens 127, 130 have more have more granitic texture with scattered pyroxenes.
102	<u>Amphibolite</u> —Fine- to medium-grain, equi-granular amphibole and feldspar, nonfoliated.

TABLE C-3

PETROGRAPHIC DESCRIPTIONS OF LICK FORK LITHOLOGIES;
POLISHED THIN SECTION

Sample Numbers		Lithology and Description
801		<u>Alkali-pyroxene-syenite</u> —Fine- to medium-grained, granoblastic orthoclase, plagioclase, quartz and altered orthopyroxene. Traces of zircon, pyrrhotite, ilmenite and hematite. Sample #131 contains amoieboid garnet.
802		
805		
806		
807		
808		
821		
131		
809		<u>Hornblende-peridotite</u> —Fine- to medium-grained, polygonal granoblastic hornblende, olivine serpentine, orthopyroxene, clinopyroxene, and biotite. Sulfides are pyrrhotite, marcasite, pentlandite, violarite and chalcopryrite. Oxides consist of spinel with traces of magnetite-ilmenite and goethite. Silicates are partially altered to uralite, serpentine and sericite.
D-1		
D-2		
D-3A		
D-3B		
D-3C		
D-4		
D-5		
810A		<u>Gabbro</u> —Fine-grained, equigranular, granoblastic polygonal, plagioclase, orthopyroxene, and clinopyroxene with traces of biotite, ilmenite and hematite.
810B		
803	815	<u>Hornblende-gabbro</u> —Fine- to medium-grained, granoblastic polygonal equigranular, hornblende, orthopyroxene, biotite, clinopyroxene and plagioclase. Traces of pyrrhotite and magnetite. Silicates altered to chlorite, sericite, and clay minerals.
809	816	
811	817	
812	818	
813	819	
814	820	

VITA

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