Petrology of mafic-layered intrusion near Lolo Pass Idaho

John Christian Jens

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PETROLOGY OF A MAFIC-LAYERED INTRUSION

NEAR LOLO PASS, IDAHO

By

John C. Jens

B.A., University of Iowa, 1970

Presented in partial fulfillment

of the requirements for the degree of

Master of Science

UNIVERSITY OF MONTANA

1972

Approved by:

[Signatures]

Chairman, Board of Examiners

Dean, Graduate School

Date

Dec 27, 1972
ACKNOWLEDGEMENTS

Drs. David Alt and Donald W. Hyndman suggested this study, provided needed encouragement and advice, and made helpful suggestions throughout the work. Dr. John Nold also encouraged this study and provided location information.

Interest and criticisms by the discussions with Dr. Tom Margrave are also appreciated. Dr. Gary Crosby supervised and assisted a reconnaissance gravity survey along U.S. 12 over the study area.

Jim Salmonson assisted in the field work on several occasions. Special thanks is due Dick Benoit without whom samples at the deep road cut along U.S. 12 could not have been collected.

Ward Development Company provided a geonics electromagnetic instrument for field work as a mapping aid. Pat Clarida typed the manuscript. Support from my wife, Donna, to complete this study is also acknowledged.
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CHAPTER I
INTRODUCTION

Purpose of the Study
The purpose of this study is to present petrographic evidence to support the hypothesis that the amphibolite-ultramafic body three miles south of Lolo Pass is a metamorphosed mafic layered intrusion and to further elucidate its petrogenesis.

Nature of Investigation
The index map (Figure 1) gives the location of this study. Plate 1 is the result of reconnaissance mapping carried out by the author. The most notable change from the excellent map of John Nold (1968) is the connection of the three eastern segments into one body. Two minor adjustments are the Crooked Fork Rhyolite Dike found near the center of the western half and the xenolith(?) at the very western end.

Due to the disrupted nature and very poor exposure, study was concentrated on the excellent 35 m. deep outcrop on U.S. highway 12 (Point 4306 and see Plate 2), and to a lesser extent to two logging road cuts, one located at point 4480 west-northwest of the U.S. 12 outcrop and the other at point A two miles east (see: Plate 1).

Approximately 50 samples were collected from these three outcrops and plotted on photographs of the appropriate outcrops. These samples were all thin sectioned and examined.
Index map showing the study area, the outline of the Idaho batholith, and pertinent areas of recent investigations.
GEOLOGY OF THE ULTRAMAFIC LAYERED INTRUSION
RECONNAISSANCE BY JOHN NOLD, 1968
DETAIL BY JOHN JENS, 1972
EXPLANATION

Qal
ALLUVIUM
(CROOKED FORK PLUG — rhyolite)
assoc. rhyolite dikes and sills.

Lb
LOLO HOT SPRINGS BATHOLITH — granite and quartz monzonite.

peg
PEGMATITITES

BFs
BRUSHY FORK STOCK — quartz diorite and granodiorite. BFs — assoc. quartz diorite and diorite dikes and sills

qd
QUARTZ DIORITE DIKES AND SILLS

om
ORTHOMPHIBOLITES — some
am
amandine bearing

uli
ULTRAMAFIC LAYERED INTRUSION

csg
CALC-SILICATE GNEISS AND SCHIST —
csb — brecciated

q
QUARTZITE
An additional 50 thin sections were cut from over 200 specimens of float.

**General Description and Definition of Terms**

In many handspecimens, as in outcrop, the amphibolite is visibly layered. At first observation the layering appears to be due to a schistosity defined by prismatic to acicular hornblende. However, on closer examination many layers are compositionally distinct, being ultramafic in that they contain less than 30% leucocratic minerals (Wyllie, 1967 p.1). Most layers are melanocratic to mesocratic, being various shades of gray and gray-green to black. Weathering is earthy brown in most cases.

Boundaries between layers are generally very sharp in outcrop (Plate 3) and are only one to three grains wide in thin section. However, some layers are gradational (Plates 5a, 6b, & 7) but have sharp upper and lower contacts; these will be discussed later under layer types.

The term "layering" is used exclusively in accordance with the suggestion of Wager and Brown (1968, p.V and p.544) that bedding and stratification are terms to be restricted to the usual sedimentary rocks.

**Previous Work**

Previous work done on this study area is confined to that reported by Nold (1968). Brian White (1969) did a structural
study to the northeast, providing a more detailed structurally pertinent study within Nold's dissertation area. Other work generally adjoining Nold's area is drawn from in an attempt to put an age on the intrusion and later metamorphism.

**General Geologic Setting**

Nold's work (1968) provides an excellent description of the geology centering on the Lolo Pass area. The Idaho batholith to the south and other igneous bodies of a granitic to quartz-dioritic composition are intruded into regionally metamorphosed Precambrian Belt units from greenschist facies (biotite zone) in the north to upper amphibolite facies (sillimanite zone) along the eastern portion of the area.

This study area lies within the intermediate plagioclase zone (lower amphibolite facies) and may be metamorphosed to at least this facies. A quartz diorite—the Brushy Fork stock—intrudes the orthoamphibolite in several areas especially well seen in the outcrops along U.S. 12.

The main country rocks surrounding the orthoamphibolite are calc-silicate gneiss. This gneiss is correlated with the Wallace Formation as set forth in arguments presented by Nold (1968, p.101-104).

Numerous pegmatite dikes disrupt the ultramafic intrusion and several dikes of Crooked Fork Rhyolite invade it.

White (1969) distinguished five major deformational events or phases (p.42) for the area, the first being
contemporaneous with regional metamorphism. The remaining four are associated with faulting.

Subsequent intrusions in the area have probably aided retrogressive metamorphism via disseminated fluids given off during their intrusion. The regional metamorphism is agreed to be Mesozoic (R.R. Reid verbal communication to Hyndman, Oct. 1972).
CHAPTER II
MINERALOGY

The thin-section characteristics of the minerals observed are summarized in Table 1.

Amphiboles

Hornblende is the most wide-spread and abundant mineral found, and in almost every instance excepting the poikilitic habits, is remarkably euhedral to subhedral (Plates 11a, 11c, 13c and 13d).\(^1\) Its size and shape vary from acicular to large stubby crystals to large poikicrysts. The percentage of hornblende also varies greatly from 15 to 95%. Its pleochroic scheme in browns and greens doesn't vary much from sample to sample since its composition has been evened out by metamorphism. A second hornblende with bluish-green pleochroism was also noted (also reported by Nold, 1968, p.97) in many thin sections, occurring as small, euhedral prisms and/or as rims on the larger hornblende. The change from brown to bluish pleochroism is gradational, but where the amphibole finally becomes actinolite, there is a sharper boundary between actinolite and hornblende (Plate 13c). The hornblende locally contains simple twins (see Plates 15a and 17a).

\(^1\)Microphotographs (Plates 11a to 18b) referred to are found at the end of the text arranged in the order of layer types discussed in the next section.
<table>
<thead>
<tr>
<th></th>
<th>PLEOCHOISMO</th>
<th>2V</th>
<th>Z A C</th>
<th>DISPER.</th>
<th>SIZE (mm)</th>
<th>SHAPE</th>
<th>ZONING</th>
</tr>
</thead>
<tbody>
<tr>
<td>HORNBLende 1</td>
<td>x = lt yellow tan</td>
<td>70-90°</td>
<td>20-17°</td>
<td>r ≤ v weak</td>
<td>0.5x5</td>
<td>eu — an</td>
<td>rimmed by Hb 2, eu core w/ poik. rim</td>
</tr>
<tr>
<td></td>
<td>y = grn—grnbrn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>z = grnbrn—brngrn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HORNBLende 2</td>
<td>x = clar—lt tan</td>
<td>70-90°</td>
<td>17-15°</td>
<td>r &gt; v mod.</td>
<td>0.1-1</td>
<td>eu — an</td>
<td></td>
</tr>
<tr>
<td></td>
<td>y = lt grn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>z = bluish grn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACTINOLITE</td>
<td>x = clar</td>
<td>90°</td>
<td>16-14</td>
<td>v. weak</td>
<td>1</td>
<td>eu — an</td>
<td></td>
</tr>
<tr>
<td></td>
<td>y = clar—lt grn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>z = lt grn—lt blgrn</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANTHOPHYLLITE</td>
<td>x = clar; z = tan</td>
<td>85°</td>
<td>56-50°</td>
<td>r &lt; v mod</td>
<td>0.1-1</td>
<td>eu — sub lamellae</td>
<td></td>
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<td></td>
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<tr>
<td>DIOPSIDE</td>
<td>v.v. slight grn</td>
<td>40-42°</td>
<td>30-40°</td>
<td>r &gt; v weak</td>
<td>0.25-1</td>
<td>eu — sub lamellae</td>
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<tr>
<td>HYPERSTHENE</td>
<td>x = intense pink</td>
<td>55-60°</td>
<td>35-40°</td>
<td>r &gt; v weak</td>
<td>0.25-1</td>
<td>eu — sub lamellae</td>
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<tr>
<td></td>
<td>y = pale yellow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>z = pale smoky grn</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EPIpOTE</td>
<td>x = clar—yellowish</td>
<td>80-90°</td>
<td>parallel</td>
<td>r &gt; v weak</td>
<td>0.1-1.5</td>
<td>sub—an</td>
<td></td>
</tr>
<tr>
<td></td>
<td>z = bright yel.—grn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLINOZOSITE</td>
<td>clar</td>
<td></td>
<td>30°</td>
<td>r &lt; v strong</td>
<td>0.1-0.7</td>
<td>sub—an</td>
<td></td>
</tr>
<tr>
<td>CHLORITE</td>
<td>x = tan or grn</td>
<td>0-10°</td>
<td></td>
<td></td>
<td>0.1-1</td>
<td>sub—an</td>
<td>alternat Mg-Fe-rich sheets</td>
</tr>
<tr>
<td></td>
<td>z = grn or tan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BIOTITE</td>
<td>x = tan</td>
<td></td>
<td>10°</td>
<td></td>
<td>0.1-1</td>
<td>sub—an</td>
<td></td>
</tr>
<tr>
<td></td>
<td>z = redbrn—grnbrn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUSCOVITE</td>
<td>clar</td>
<td></td>
<td>30°</td>
<td>r &lt; v weak</td>
<td>0.1-0.7</td>
<td>eu — an</td>
<td></td>
</tr>
<tr>
<td>PLAGIOCLASE</td>
<td>albrite; pericline; Carlsbad—simple &amp; complex</td>
<td>70-90°</td>
<td></td>
<td></td>
<td>0.1-3</td>
<td>eu — sub normal reverse oscillatly patchy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TWINNING</td>
<td></td>
<td></td>
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<td>ORTHOCLOSE</td>
<td>residual melt</td>
<td>30-90°</td>
<td></td>
<td>r &lt; v strong</td>
<td>0.1-0.5</td>
<td>an</td>
<td></td>
</tr>
<tr>
<td>SPHENE</td>
<td>not recognized in hypersthene-bearing thin sections</td>
<td>40°</td>
<td></td>
<td>r &gt; v strong</td>
<td>0.1-1</td>
<td>eu — an</td>
<td></td>
</tr>
<tr>
<td>APATITE</td>
<td>residual melt + U</td>
<td></td>
<td></td>
<td></td>
<td>0.01-0.5</td>
<td>eu</td>
<td></td>
</tr>
<tr>
<td>QUARTZ</td>
<td>residual melt strained + U</td>
<td></td>
<td></td>
<td></td>
<td>0.05-1</td>
<td>an</td>
<td></td>
</tr>
<tr>
<td>MAGNETITE</td>
<td>opaque</td>
<td></td>
<td></td>
<td></td>
<td>0.05-1</td>
<td>eu — an</td>
<td></td>
</tr>
<tr>
<td>PYRITE</td>
<td>opaque, cubes</td>
<td></td>
<td></td>
<td></td>
<td>0.1-10</td>
<td>eu</td>
<td></td>
</tr>
<tr>
<td>HEMATITE</td>
<td>blood-red</td>
<td></td>
<td></td>
<td></td>
<td>0.05-1</td>
<td>an</td>
<td></td>
</tr>
</tbody>
</table>
Much of the hornblende is believed to be metamorphic in origin, replacing earlier mafic minerals, and pseudomorphs an igneous texture (Plates 17a and 18a). Hornblende replaces diopside from within as blebs which are optically continuous throughout the individual diopside. In plates 16a and 16b hornblende is seen rimming and replacing hypersthene.

In some layers there appear to be inclusion-free cores near the center of large hornblendes (Plates 13d, 16a and 17a). This core is generally choked with laths which have the appearance of exsolved plates, possibly the exsolution of another amphibole. These brown platelets occur along at least one and possibly two planes within the hornblende (Plate 17a). This appearance of similar exsolution lamellae of diopside from hypersthene was made strikingly evident to the writer upon examination of thin sections from the Giles Complex area of central Australia (courtesy of Dr. J.L. Talbot). The platelets in the hornblende are too small and are masked by the hornblende making identification impractical at this time. Several authors (Klein, 1968; Jaffe et al, 1968; Ross, Papike & Weiblen, 1968) have reported exsolution lamellae in amphiboles and coexistence of the same. They reported the following pairs: anthophyllite-hornblende; cummingtonite-hornblende; anthophyllite-cummingtonite. The actinolite-hornblende exsolution pair does not seem to have been described; however, a miscibility gap has been (this paper see below, various authors reported in Deer, Howie, and Zussman, 1963 p.304-305; Klein, 1967).
One thin section, sample OJh, contains a possible occurrence of anthophyllite. In this specimen the hornblende (pleochroism light green and light brownish-green) rims another amphibole tentatively identified as actinolite on virtual absence of pleochroism and a fibrous appearance. Further examination revealed another fibrous to prismatic amphibole which appears to be anthophyllite.

This singular occurrence of anthophyllite amplifies the suspicion that the exsolution lamellae in the hornblende are anthophyllite in this specimen based on the literature cited above (especially Jaffe et al, 1968 and Ross, Papike and Weiblen, 1968). Where this suspected anthophyllite occurs with hornblende, the hornblende contains very thin and fresh-appearing exsolution lamellae. This is in contrast to the platy coarser exsolution in the hornblende cores. The latter is probably of igneous origin; the former, metamorphic. Further support for metamorphic origin of the former is the similar thin exsolution seen in the actinolite.

This thin section (OJh) is thus distinct and unique in two ways, (1) two distinct hornblende types are found with their respective exsolution types and (2) the miscibility gap between hornblende and actinolite-tremolite is well displayed. The explanation postulated is that the platy exsolution hornblende with stronger brown pleochroism is early, possibly primary, and the rim of green pleochroic
hornblende around the actinolite-tremolite is an expression of increasing metamorphism. This latter feature has been described by several authors reported in Deer et al (1963, pp.304-305) and by Gemuts (1971) where increasing grade of metamorphism is related to a sharp change from actinolitic to hornblendic composition followed by increasingly deepening of the hornblende pleochroism from bluish green to greenish brown. The reverse relationship is shown in other thin sections examined (Plate 13c) where the actinolite is apparently retrogressive.

The hornblende with platy exsolution cores also appears to have grown poikilitically (or poikiloblasitically) into the surrounding hypersthenne and diopside (Plate 17a). Rarely a few hypersthenne and/or diopside crystals are seen within the core. These hornblendes are not compositionally zoned as viewed from pleochroism or extinction angles. However, where hornblende and diopside comprise a layer the hornblende is commonly bleached around the rim and around inclusions (Plate 13). These observations are discussed below.

Actinolite generally is seen as a retrograde feature forming a mortar texture around the hornblende. The shape of the actinolite is acicular to prismatic with occasional diamond-shaped end sections where the mortar texture is well developed. It is recognized by its pale green pleochroism and smaller extinction angle than hornblende.
Pyroxenes

Diopside was first observed by Nold (1968) in a rock consisting of 23% diopside and 75% hornblende and since identified in many specimens. The diopside is typically very light green and in one or two instances has an exceedingly weak pleochroism in the light green shades. It is characterized by corroded to euhedral shape and by abundant inclusions of hornblende to which it is apparently altering (Plates 13a, 13c, 15a and 18b). There is a slight decrease in ZAc when hypersthene is present, apparently reflecting the slight relative depletion of magnesium and iron in the system caused by the formation of the orthopyroxene as an additional phase in the magma. The diopside is considered essentially a primary mineral. This is substantiated by some slight zoning noted in several samples (see eg: Plate 15c). Six successive zones can be distinguished on the basis of "inclusions" which are for the most part exsolution lamellae. The zones are illustrated in the following diagram (see also Plate 15c):

```
50% Host, 50% Lamellae
80-90% Host, 20-10% Lamellae
65% Host, 35% Lamellae
95% Host, 5% Lamellae
75% Host, 20% Inclusions, 5% Lamellae
90% Host, 8% Inclusions, 2% Lamellae
```
This large crystal (1 mm. across) reflects changes in temperature and/or melt composition during its crystallization history. The zones with exsolution lamellae reflect the times when the system was above the solvus for diopside and orthopyroxene (OPX), that is the temperature was higher such that the OPX molecule was dissolved in the diopside system. The exsolution-free zones correspond to times when slightly lower temperature on the system permitted crystallization of diopside relatively free of OPX molecule. A supercooling mechanism such as that which operated in the Skaegaard Intrusion provides an explanation of the zoning (Wager and Brown, 1968, p.221-223). The diopside nucleated near the floor of the magma chamber and grew at a temperature above the solvus, thus being OPX-rich. Due to convection the grain rose to the top of the chamber where the magma was supercooled. The diopside then grew OPX-poor with the OPX exsolving in the core. Upon reaching the chamber floor the diopside would crystallize another OPX-rich zone. This is caused by loss of heat from the crystal pile into the supercooled magma which would drive the temperature above the solvus. Continued circulation within the magma chamber would cause additional OPX-rich and OPX-poor zoning. Thus, the diopside crystal in Plate 15c would have made at least three cycles before being deposited.

The (100) twin plane is present in numerous diopside crystals. One is seen in the grain just described (Plate 15c).
Here the exsolution lamellae appear parallel to the twin plane, giving two possibilities: (1) pigeonite inverted to hypersthene with augite lamellae and (2) host augite (in this case a diopside-augite composition) with hypersthene lamellae. The latter pertains here since the host is a clinopyroxene and not an orthopyroxene. This is also based on the optical orientation of the host mineral (Hess, 1960, p.38).

The orientation of these exsolution lamellae within the host indicates the temperature of the magma to be approximately 1100°C (Hess, 1960, p.39-40).

The hypersthene forms euhedral to subhedral crystals (Plates 15c and 16b) and is easily identified by its unmistakeable pleochroic scheme (Table 1). According to Deer et al (1963, p.29) and Heinrich (1965, p.202, 206-207) the composition of this orthopyroxene based on dispersion and 2V would be En$_{87.5}$ to En$_{82}$ or a bronzite (until further confirmation hypersthene will be used as a general term for this pleochroic orthopyroxene).

In prismatic and end sections of hypersthene, exsolution lamellae of diopside can be seen (Plates 15a, 15c, 17b). These are oriented parallel to (100) and impart an apparent undulose extinction. Zoning can best be seen in end sections (Plate 17b, left and below center). Although this is analogous to the zoning seen in the diopside, it
bears a relationship in composition. This zoning coupled with the fact that the euhedral crystals have a stubby habit implies an igneous origin for the hypersthene (MacKenzie, 1960). A few elongate crystals of hypersthene are seen (Plates 15b and 15c). MacKenzie (1960) also reported elongate hypersthenes but of an extreme tabular habit which he explained as intragranular translational gliding upon solid intrusion. Only those grains which were oriented in the proper direction would experience the gliding, hypersthene being fairly refractory and rigid (p.313-314). Exsolution then followed emplacement. However, this is not the case here. A probable explanation must include the fact that the position of the exsolution lamellae in the hypersthene are zoned with respect to an end section and extend the entire length of the crystal. Crystallization from a magmatic melt affords the simplest explanation. Growth of the crystals may be most rapid along the C-axis since the silica chains parallel this direction (Deer et al, 1963, p.11).

**Plagioclase**

Plagioclase is readily identifiable in thin section because of its characteristic twinning. The most abundant twins and twin combinations are albite, carlsbad, pericline, carlsbad-albite, and, carlsbad-albite-pericline. Subramaniam (1956) in a study of the twin laws of plagioclase in the Sittampundi Complex outlined criteria for
distinguishing between metamorphic twins and igneous twins. Carlsbad-albite and carlsbad twins are considered indicative of igneous parentage, and albite and pericline twins more typical of metamorphic parentage.

Where metamorphism is not extensive such as sample OJP, the more complex twins indicating igneous parentage are very abundant (Plate 18a). The carlsbad-albite twin in this grain, when considered with the embayed euhedral shape and zoning definitely points to an igneous origin; the crystal measures 2 x 3 mm. Spry (1969, p.158) states, "It is concluded that most embayed megacrysts (large crystals) in metamorphic rocks are relict and pre-metamorphic and that they were formed by igneous crystallization followed by partial dissolution rather than by solid state coalescence."

The layer containing this grain is well preserved in that numerous large (1-2 mm.) plagioclase crystals show continuous normal zoning and several display oscillatory zoning as well as complex twinning.

Another thin section of OJP reveals that the large plagioclase laths form an igneous lamination. The following individually described plagioclase crystals display additional evidence for an igneous parentage. One grain contains a calcic core with an irregular but rounded outline as if corroded. This core displays a normal continuous zoning and several faint polysynthetic twins. The rim, however, appears to be more sodic, is not zoned, and
shows albite and pericline(?) twins which are not continuous with the twins in the core. This appears to be an extreme example of patchy zoning which is attributed exclusively to rocks of an igneous origin (Vance, 1965, Jorgenson, 1971).

A second grain displays well developed oscillatory zoning; nine zones were counted including the core and show an overall normal trend. Both oscillatory zoning and normal trend are generally taken as indicative of igneous origin especially if viewed together (Hyndman, 1972, p.159, 362).

It is also noted that rings of diopside and hypersthene crystals could be seen around larger plagioclase crystals within the large poikilitic hornblende. These rings are usually at one grain diameter, 0.5 - 1.0 mm. from the plagioclase. The significance of these rings is not clear to the author.

Other layers which contain plagioclase bear other evidence which coupled with twin relationships point toward an igneous origin. Several samples contain bent twins (Plate 12a) which are taken as metamorphic and rims of less calcic plagioclase giving a normal zoning to the crystal (Plate 11d). This latter is probably of metamorphic origin; however, the replacement process may have been aided by accumulate growth. Some layers where euhedral to subhedral laths of
plagioclase occur do not appear to carry this rim and are possibly remnant accumulate layers (Wager & Brown, 1968—various examples given). A striking resemblance is seen between the large grain in Plate 11d and one in Fig. 17a in Wager & Brown (1968, p. 35), which is due to accumulate growth.

A second distinctive occurrence of plagioclase is shown in Plate 12a. Here large plagioclase crystals have gone to a mortar texture. These areas of small plagioclase crystals have the general outline of a large (2 x 3 mm.) plagioclase lath (part of one is shown in the photo). It can be seen that parts of twins are continuous from fragment to fragment, and that the extinction of the fragments is generally coincident. Upon insertion of a gypsum plate the relative optical continuity is spectacular. It is clear that a larger crystal has broken up since crystallization.

Another occurrence of plagioclase is clearly igneous in origin. Interstitial plagioclase occurs in a layer of large (3 - 5 mm.) euhedral equant hornblende crystals with occasional diopside. In Plate 14a interstitial plagioclase is seen to have oscillatory zoning and appears to have crystallized from a residual melt trapped between the large grains. The final material crystallized was probably quartz. This could in gross terms be called a granophyre as very rare orthoclase is also found in these
residual melt areas. A similar deposition of quartz, orthoclase, and apatite is reported for the Skaergaard layered intrusion, Greenland (Wager & Brown, 1968, p.60). (Refer also to apatite section in this study.)

A fourth occurrence of plagioclase with an extensive poikilitic habit is also found (Plate 16b) and bears close resemblance to poikilitic plagioclase described in the Rhum Intrusion (Wager & Brown, 1968, p.265-267, Figure 149, p.266) and in the Stillwater Complex (Hess, 1960, Plate 3, Fig. 2, and Fig. 20, p.84, and Wager & Brown, 1968, Fig. 180, p.323). Comparison of Plate 16b with the cited examples of the two other complexes is excellent except that in this study the primary cumulate is hypersthene and not olivine. Euhedral orthopyroxene going to subhedral to anhedral is indicative of heteradcumulate growth (Wager and Brown, 1968, p.318-319). Plate 16b, on this basis, shows heteradcumulate growth in several domains. They also note that this type of texture is formed by acumulate growth of both primary cumulate and intercumulate phases via a diffusion mechanism in a slowly cooling melt-crystal environment. Thus an igneous parentage is indicated for the plagioclase.

**Accessory Minerals**

Questionable orthoclase was observed in several thin sections. Some undoubted orthoclase is seen in the residuum of the coarse hornblende rock. Quartz is also found in this
residuum, has a strained appearance and gives an anomalous interference figure. Other quartz found is usually associated with hornblende as a by product in its transformation from other minerals.

Epidote (pleochroic) and clinozoisite (colorless with anomalous low birefringence) occur as alteration products of plagioclase and possibly of hornblende. Although many subhedral are found, only one euhedral crystal was seen. The common appearance for both is a patch work of crystals varying slightly in orientation and producing a strained effect under crossed-nicols. The amount of both in a thin section is determined by the extent and type of alteration in the rock.

The phyllosilicates are widespread, with at least one of three found in virtually every thin section; these being chlorite, biotite, and muscovite. Chlorite being an alteration of hornblende and biotite, gives a wide range of anomalous blues to mauves reflecting variations in Mg and Fe$^{+2}$, often within the same crystal. Biotite is found as an alteration of hornblende although this association isn't always apparent. Phengitic mica occurs as a sericitic alteration of plagioclase and as saussurite where fine grained and associated with epidote. Where the alteration is extensive the white mica begins to form good "books" and has a higher birefringence; this can be termed muscovite (Plate 12b).
Apatite is a sparse accessory mineral occurring throughout many of the samples. Its most noteable occurrence, of igneous origin, is in the coarse hornblende layers where it is found as large (0.3 - 1 mm.) euhedral crystals interspersed in the intercumulate residuum (Plate 14b). In other layer types it is generally less than 0.1 mm. in length and considered metamorphic in origin.

Except for hypersthene-bearing thin sections, sphene is found as an accessory mineral in virtually every thin section examined. It is here generally considered to be mainly of metamorphic origin as some is seen to be exsolved along hornblende cleavages (Plate 14b) and also intergrown with magnetite (see: Magnetite). Generally intergranular, the sphene is anhedral and locally euhedral. Rarely observed were rutile and "leocoxene."

Other minerals noted were a single grain of green spinel in one thin section and traces of calcite in two thin sections.

Opaques

The most abundant opaque mineral is magnetite. This may be an ilmenomagnetite as certain layers contain intergrowths of sphene and magnetite. In several cases the sphene appears to be corroding the magnetite and in others appears as fine to coarse linear intergrowths within the host magnetite extensively replacing it, rutile(?) is found as blebs within the sphene. This coupled with the fact that rutile is very rare
and lecocxene associated with the rutile even rarer leads
the writer to believe that the magnetite is titanium rich.

The magnetite is anhedral and intergranular for the most
part and euhedral where apparently of metamorphic origin.
Hornblende commonly contains blebs of magnetite, the amount
depending on degree of metamorphicism and original composition
of the hornblende.

Pyrite, present in trace amounts only, is found in more
than half of the samples examined. Although several cubes
were found in thin section, most of the pyrite has altered
to hematite. A chlorite reaction vein at the main outcrop
contains abundant excellent cubes of pyrite, some as large
as 1 cm. but most less than 0.5 cm. on an edge. Some of
these also show octahedral faces as well, and one specimen
shows several pyritohedral faces.

Trace amounts of hematite are ubiquitous as an alteration
product of magnetite. Limonite as finely disseminated grains
is found where alteration is most extensive.
CHAPTER III
MINERALOGIC LAYER TYPES

Based on the mineralogy previously described, four basic layer compositions are found (Table 2). These are the following:

A) Hornblende-Plagioclase
B) Hornblende+Diopside-Plagioclase
C) Hypersthene-Diopside-Hornblende+Plagioclase
D) Plagioclase-Hypersthene-Diopside+Hornblende

Layer Type A) Hornblende-Plagioclase

(Plates 3a, 4 and 5) The ratio of hornblende to plagioclase in these layers is extremely variable, with 0 to 75% plagioclase and 95-20% hornblende (Table 2). The remaining percentage is usually made up by alteration and accessory minerals.

The plagioclase is generally lath shaped, forming what is believed to be a vague igneous lamination. The hornblende occurs as acicular to prismatic crystals and forms an excellent schistosity. One case of a lineation was found in the U.S. 12 road cut (marked by arrow on Plate 2). The lineation gradually diminishes upward then disappears in the middle of the layer; the schistosity, however, is maintained. A second occurrence was observed in a boulder of float containing about 15% plagioclase and pictured Plate 4b.

Contacts between layers of varying percentages of hornblende are generally sharp. In thin section they are seen
### Table 2

**Percentage Range of Minerals with Primary Texture According to Layer Type.** Parentheses indicates metamorphic mineral pseudomorphing an igneous texture. ? = possibly primary igneous phase, C = cumulate, P = poikilitic, R = residual interstitial melt, T = trace.

<table>
<thead>
<tr>
<th>Layer Mineral</th>
<th>Type-A (%)</th>
<th>Type-B (%)</th>
<th>Type-C (%)</th>
<th>Type-D (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hornblende</td>
<td>95 - 20% (C)</td>
<td>75% C</td>
<td>30 - 40% C w/ P? (Overgrowth)</td>
<td>55 - 45% P?</td>
</tr>
<tr>
<td>Hypersthene</td>
<td></td>
<td></td>
<td>50 - 30% C</td>
<td>10 - 15% C</td>
</tr>
<tr>
<td>Diopside</td>
<td>23 - 10% C</td>
<td>10 - 35% C</td>
<td></td>
<td>10% C</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>0 - 75% C</td>
<td>2 - 15% R</td>
<td>7 - 2% P</td>
<td>25 - 20% C</td>
</tr>
<tr>
<td>Quartz</td>
<td>T R</td>
<td>T R</td>
<td>T P</td>
<td>10% P?</td>
</tr>
<tr>
<td>Apatite</td>
<td>T R</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orthoclase</td>
<td>T R</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PLATE 2
OVERLAY

IDEALIZED
RHYTHMIC UNIT

A  PLAGIOCLASE-RICH

A  HORNBLENDE-RICH

D?  ________

B  GRADED LAYER(S)

B±C

C  GRADED LAYER(S)

C

D?

SOLID LINE - MAJOR UNIT
DASHED LINE - LAYER TYPE
OR SUB-TYPE
Main outcrop of layered ultramafic-mafic intrusion on U.S. 12 approximately 3 miles south of Lolo Pass. The layer marked is 1 m. thick, and the total outcrop pictured is 30 m. high. Several large and numerous small pegmatic dikes and sills disrupt the outcrop.

The overlay is a sketch of the outcrop with a schematic representation of the rhythmic layering. Layers are indicated according to the outline presented in Mineralogic Layer Types section. Also indicated are other plates and samples in this study.
Sample OJK (a float sample) showing typical boundary between two type-A layers with differing proportions of hornblende and plagioclase. Both are internally homogeneous. Top is assumed up from patterns seen in outcrop. Scale in cm. Specimen from outcrop 4480.
Closeup of the sharp contact between two type-A layers. The line is 20 cm. long and marks sample #32J. The picture is indicated on the overlay to Plate 2.
Sample OJK (as in Plate 3a) with view normal to layering to show random orientation of hornblende within a "schistosity." Scale in cm.
View is normal to layering showing coarse hornblendes with a vague lineation. Smaller (5 mm.) acicular hornblendes show a stronger lineation from the upper right to lower left. This lineated layer is only 5-10 mm. thick; the bulk of the boulder is small acicular hornblendes with a "schistosity" parallel to the layering but no lineation. Road junction at SW 1/4, NW 1/4, Sec 34, T38N, R15E. The lens cap is 5.5 cm. in diameter.
Sample OJdg (on left) with layering right way up. Coarse hornblende could be a contemporaneous mafic-pegmatite. Plag-rich layer has a sharp top boundary where a coarse hornblende layer settled one grain thick, possibly after a convective overturn. Crystallization continued then in a normal manner. In end-section the plagioclase pods in the upper layer dip toward the coarse hornblende layer at about 15°—deposition on an uneven floor or cut-and-fill(?)

Sample 14cj (on right) layer type-A with layering right way up shows a rhythmic bed with graded mineralogy according to specific gravity. Two centimeter-scale rhythmic units occur at the bottom.

Samples from outcrop #4480, scale in cm.
Sample 24aj a type-A layer from below sample 24j and is correlated with sample 68j from main outcrop. Middle of middle outcrop of U.S. 12. "Spotted" hornblende layer of type A. The spots are spherical plagioclase aggregates and show no indication of layering. Scale in cm.
to be more wavy than observed in outcrop, the change occurring over a 2 to 3 grain thickness. Plate 3a is a typical occurrence, and Plate 4a shows the randomness of the hornblende needles of the upper layer.

The right-hand sample in Plate 5a shows an exceptional example of gradation in mineralogy found in a few layers. Although much float was found, there was no definite outcrop. Also no example of such gradation was observed in the outcrop on U.S. 12.

Plate 5b shows a curious variation of this layer type—20% white plagioclase spots and 80% acicular hornblende. Very few plagioclase laths occur in the hornblende groundmass. The hornblende tends to wrap around the plagioclase crystal aggregates as pictured in Plate 12b. In a few of the spots, hornblende is seen growing as euhedral needles.

This layer type varies from a few centimeters (Plate 5a) to almost two meters thick (Plate 2).

**Layer Type B) Hornblende + Diopside-Plagioclase**

This layer type appears rather striking and is unusual. It contains large (3 - 7 mm.) euhedral hornblende which, where diopside is present, display a prismatic form and well define the layering (Plates 6a and 6b).

Where diopside is abundant it generally comprises 23-25% of the layer along with 75% hornblende and 2% plagioclase (Table 2). When diopside dies out, plagioclase is the main
Sample 33J, a type-B layer from main outcrop on U.S. 12. 
Hornblende: black crystals; Diopside: medium gray; Plagioclase: white. Scale in cm., top is up.
Sample OJc, a type-B layer from main outcrop on U.S. 12 showing gravity stratification of hornblende. Black is hornblende, medium gray is diopside, white is plagioclase. Scale in cm., top is up.
Closeup of small-scale rhythmic layering in layer type-B indicated on the overlay of Plate 2. The lower part of each layer is coarse hornblende, the top enriched slightly in plagioclase. Two such layers indicated are a total of 10 cm. thick. The attitude is correct with top of layers to the upper right.
interstitial material, being poikilitic to the hornblende. Diopside on the other hand occurs as euhedral to subhedral grains crowded between the hornblende crystals (Plates 13a, 13b, 13d & 15b). The diopside as previously described contains abundant inclusions of hornblende; very few exsolution lamellae were noted.

Plate 6a shows one type of a possible rhythmic layer. The layer at the bottom, containing only interstitial plagioclase, is sharply abutted by the layer above, containing minor interstitial plagioclase and abundant diopside. This then is seen to grade into the layer above where interstitial plagioclase rapidly becomes abundant to form a layer similar to the one at the bottom.

Due to a convective overturn the layer is buried beyond the reach of the diffusion mechanism connecting the intercumulate melt with the parent magma and growth of diopside is minor. This convective overturn would effectively remove lower layers from extensive reaction with the magma allowing crystallization of a granophyre (e.g. Plate 14a and Plagioclase section).

Plate 13b is from the center of the diopside-rich layer and resembles an inverse heteradcumulate. Instead of the interstitial material being anhedral and poikilitic it is euhedral and a primary cumulate. The hornblende is then the equivalent of the interstitial material in a normal heteradcumulate. The large hornblende nucleated after or
at the same time as the diopside but grew more rapidly, including some diopside which grew much more slowly or not at all due to rapid removal by the hornblende of components from the system. Plate 14a shows that the diffusion mechanism does operate as shown by the plagioclase oscillatory zoning. Plate 13b was taken of a sample from near the "16" on the scale of Plate 6a.

Another type of gradational layer in the Hornblende
Diopside-Plagioclase layer type is shown by the sample in Plate 6b. Here, however, the characteristic thing is that the hornblende appears as a rhythmic layer within the compositional layering. The lower three-fourths of the specimen is rich in interstitial diopside grains and the upper one-quarter is more plagioclase-rich. The hornblende is apparently gravity stratified and stratified also in habit from large stubby crystals at the bottom of the layer to medium prismatic to small acicular crystals at the top of the layer, which also shows a lineation.

This layer type is usually 10 cm. to 1.5 m. thick.

Layer Type C) Hypersthene-Diopside-Hornblende+Plagioclase

This layer type resembles the graded layer described in layer type-B above, as can be seen from the sample shown in Plate 7. The hornblende is graded in size and habit similar to Plate 6b; however, its percentage is only half as great as the graded type-B layer. Diopside remains
Sample 119J is a type-C layer and is composed of hornblende (large black crystals)—hypersthene and diopside (small fine grained crystals)—plagioclase (not seen in hand specimen). The specimen displays a gravity stratification of hornblende similar to that pictured in Plate 8. Scale in cm., top is up.
SE 1/4, SW 1/4, NW 1/4, SEC 34, T38N, R15E on lowest logging road. The boulder may or may not be in place. Rhythmic graded units of type-C showing a probable contemporaneous slump feature at right of the picture. Note the following sedimentary features: wedging out of a layer between the two dark layers just above center and undulose layer below indicating uneven floor or uneven compaction of the crystal pile. For scale the hammer is 33 cm. long. Top is up.
Closer view of upper right of Plate 8a. A mafic pegmatite vein wedges out to the left at the bottom of the blue hammer handle (19 cm. for scale), probably formed as the block below slumped. A healed fracture (indicated by arrows) is dilated by the mafic pegmatite vein. The offsetting "fault" is indicated by several dashes. For further explanation see text.
Closeup of Plate 8b showing two rhythmic units with gravity stratified hornblende, relic of an earlier mafic assemblage(?). Cumulate diopside and hypersthene occur interstitial to the large hornblende and as inclusions within the hornblende. The blue handle is 19 cm. long.
about the same percentage but in thin section is seen to increase slightly from the bottom to the top of the layer. Hypersthene decreases correspondingly. The hornblende is more poikilitic than seen in handspecimen. Plates 17a and 17b show diopside and hypersthene grains within the poikilitic hornblendes near the bottom of the layer. Poikilitic plagioclase is also more abundant in the lower 4/5 of the layer.

A similar rock is found in the outcrop on U.S. 12 (eg: Plate 16a). The only difference between these two samples is the relative abundance of the hypersthene and diopside. Sample 57J could be correlated as being just below sample 119J based on increased hypersthene and poikilitic plagioclase, increased hornblende size and appearance of cores, and decreased diopside content.

This type and style of layering make up the rhythmic-graded beds shown in Plate 8. Such repetitive layering characterizes a differentiated layered intrusion as distinct from a differentiated sill such as the classic Palisades Sill in New Jersey (Wager & Brown, 1968, p.545.).

These rhythmic layers appear to vary only from 10 cm. to 20 cm. thick.

Layer Type D) Plagioclase-Diopside-Hypersthene+Hornblende

This layer type contains the large poikilitic crystals of hornblende of which Plate 9 is an outstanding example.
Sample OJP collected as float from the south end of the main outcrop on U.S. 12. A type-D layer with top undetermined. The large dark patches are hornblende poikicocrystals and form a planar feature taken as parallel layering—in thin section an igneous lamination of plagioclase laths is observed parallel to this feature. Scale in cm.
The parallel structure within the layer is best seen at this scale. Plates 18a and 18b are from this specimen (OJP).

The poikilitic hornblende varies from 0.5 x 0.3 cm. to 3 x 2 cm., the smaller grains being more plate-like and the larger being prismatic as can be seen by cleavages reflecting light.

Plagioclase, diopside, and hypersthene occur as the inclusions and interstitial cumulate. These are mainly euhedral to subhedral as shown in Plates 18a and 18b. Diopside is seen altering to hornblende from within and where the diopside occurs as inclusions it is highly corroded and embayed. Plagioclase is embayed but less so. Hypersthene is the least affected and is more often corroded than embayed.

The smaller plates of hornblende occur interstitial to the plagioclase-diopside-hypersthene between the large hornblende poikiliths, which outline the layering. Plagioclase is evenly distributed throughout and displays an excellent igneous lamination parallel to the plane of the large poikiliths. The plagioclase, as stated above, displays remarkable preservation of igneous textures; several of these being, euhedral megacrysts, complex twinning attributed to igneous origin, euhedral oscillatory zoning, and patchy zoning (see Mineralogy: Plagioclase).
Although much float was found, this layer type was nowhere directly observed in place. From float specimens found the thickness could vary from more than 10 cm. to more than 2 m.

The order of abundance of these layer types is the order in which they were described. Layer type-A is by far the most abundant found, especially in view of its great range of compositional variation. The other three types are subequally abundant and are also widely distributed. The percentage of these layer types characterizes the intrusion as ultramafic to mafic.
CHAPTER IV
MEGASCOPIC FEATURES

Several items seen on the outcrop scale also point toward an igneous origin for this mafic-ultramafic body.

The most obvious characteristic in the main outcrop on U.S. 12 (Plate 2) is that the layer contacts are quite sharp and very planar, and the thickness of layers does not vary along strike. Due to the disrupted nature of the amphibolite, the greatest distance a layer could be traced was approximately 60 meters. This was the layer from which the sample shown in Plate 5b was collected. This layer is approximately 40 cm. thick and can be apparently correlated in the deep outcrop on U.S. 12, 400 m. to the south, with a similar layer of approximately the same thickness. Here the layer is traceable only for 10 meters.

The argument might be made that this is a metamorphosed shaly limestone or calcareous shale sequence. However, the metasomatism or metamorphic differentiation would need to occur over several meters and be a repetitive mechanism, as it can be demonstrated that at least three well-defined rhythmic units can be seen in the main outcrop on U.S. 12 (see overlay to Plate 2). The lower half of each unit consists of grossly-graded layer types—B and —C which then grade into the nearly pure hornblende member of layer type—A.
There is a sharp boundary; the upper half is a uniform section of layer type-A with a sharp upper contact and then repetition of the unit.

A metasomatic origin would have to also account for the fact that the vast majority of layer types found are in the ultramafic to mafic range. This would imply wholesale diffusion of many constituents which for this area cannot be demonstrated (Hyndman, Alt, & Nold 1967). Most diffusion would have to be along the strike to the beds with little diffusion across the bed and even less or no diffusion between separate beds. Such a restrictive mechanism seems unrealistic.

The diffusion mechanism also would have to explain graded layers seen in Plates 8a, 8b, & 8c. The rhythmic nature of these graded layers plus the rhythmic nature of the series of units displayed at the main outcrop is truly indicative of differentiation of a magma (Wager & Brown, 1968, p.545).

Accentuation of the layering by metamorphism under stress to produce the schistosity and lineation is also a possibility to be considered (Bowes, et al, 1964). However, one layer (sample 52) in the center of the main outcrop (see overlay to Plate 2) displays a lineation of hornblende which becomes increasingly random as one goes up the layer and appears to die out entirely once the center of the layer is passed. The foliation remains. From this it is argued that
the structure is a primary one being the result of a strong convection current becoming weaker with time.

Such a convection system is suggestive of sporadic "fast" currents resulting from convective overturn and was also suggested as operative in the Skaegaard Intrusion (Wager & Brown, 1968, p.210-213). Termed intermittent currents by Wager & Brown (1968, p.213), the sporadic fast currents are also responsible for the gravity stratified layers when they came to rest and for the rafting of the calc-silicate xenolith described below. It is the slow, continuous currents, termed steady currents, which give the uniformity in many layers, especially the type-A plagioclase-rich layers.

A xenolith of calc-silicate gneiss approximately 1 meter wide and at least 2 meters long is found near the south end of the deep outcrop on U.S. 12 (Plates 10a, b, & c), and is conformable to the ultramafic layering. The lower contact is fairly sharp against the ultramafic layer below, the one visible end and top do not show such sharp contacts but appear as a steep gradation from calc-silicate to ultramafic. This presumably resulted from assimilation being greatest where the xenolith contacted the magma. There is no readily apparent warping of the ultramafic layer beneath the xenolith as found in the Skaergaard (Wager & Brown, 1968). However, the xenolith does resemble the xenoliths found in the Dufek Intrusion, Antarctica, where the layers of xenoliths are attributed to convective rafting (Fork & Boyd,
Location of the calc-silicate xenolith at the southern end of the main outcrop on U.S. 12. The xenolith, indicated by the arrow and outlined, is about 0.9 m. wide and at least 2 m. long. A pegmatite dike cuts the upper right corner of the picture.
Closer view of the xenolith showing its calc-silicate appearance. It is roughly outlined by dashed lines; the solid line at the base is 20 cm. long.
Closeup of the xenolith showing layering. A mafic sill of coarse hornblende-plagioclase is found at the tip of the hammer head. The base of the xenolith is indicated by the dashed line and is approximately 20 cm.
1968). If a xenolith is rafted in there should be little, if any, warping of the crystal pile.

A thin stringer of amphibolite can be seen within the xenolith paralleling the layering (Plate 10c) but cutting it in one place. A second stringer cannot be distinguished in the picture.

This xenolith is in direct contrast to the layer within which it is found, being more silica-rich than is the amphibolite.

The mafic-ultramafic body is faulted and disrupted but not folded owing to its greater competence than the country rock (Plate 2).

Numerous granitic pegmatite veins and stringers cut the mafic-ultramafic intrusion (Plates 2, 3b, and 10c). These contain quartz, orthoclase, muscovite, and locally some plagioclase and display classic textures—coarse pegmatite grading to aplite, graphic and micrographic textures, and in a few cases miarolitic cavities. The pegmatites closely resemble the rocks of the Lolo Hot Springs batholith and are attributed to it.

In addition to the granitic pegmatites, there are found numerous types of mafic veins which cross and parallel the primary igneous layering. Some are metamorphically healed fractures such as the one indicated in Plate 8b which shows as a more resistant nature than the brown weathered layers.
Many of the fractures show microshearing in that they offset layering and are the site of chloritization and epidotization.

A second mafic vein is that which could be a reaction vein formed by invading hydrothermal fluids. These are characterized by very large (1 - 2 cm.) single hornblendes with a stubby habit and abundant epidote and pyrite. Some plagioclase (albitic?), orthoclase, and quartz are also occasionally found.

Plate 8b shows at the bottom of the hammer handle a mafic vein for which the following origin is proposed.

A fracture indicated by the arrows in Plate 8b occurred during compaction of the crystal pile for which a mechanism is unknown (Beall, 1972). Dilation of a fracture parallel to the layering is achieved when the lower layers slump along a curved fracture (dashed line Plate 8b). Depression of the layers below the curved fracture by the block above is achieved along a set of microshears at a large angle to the layering. The dilation-fracture is then filled with contemporaneous fluid and the dilated-fracture (arrows) is healed during autometamorphism or a later metamorphism.

James (1971) describes contemporaneous ultramafic pegmatite dikes.

Several apparent mafic pegmatite dikes are found at Russian Creek along U.S. 12 south of the ultramafic-mafic layered intrusion (Bruce Johnson, verbal communication to author, 1972). Handspecimens and thin sections were examined by
the author graciously loaned by Bruce Johnson. These bear a striking resemblance to the mafic pegmatites in the main layered intrusion and contain large equant euhedral hornblende with interstitial plagioclase and euhedral oscillatory-zoned plagioclase with acicular hornblende. This indicated an igneous origin as stated above, with a possible affinity to the ultramafic-mafic layered intrusion as contemporaneous dikes (see also James, 1971).

Lastly, the ultramafic-mafic body as a whole is seen to be discordant, especially so locally, to the layering in the enclosing metamorphosed Wallace formation.
CHAPTER V
SUMMARY & CONCLUSIONS

The nature of the hornblende suggests that it is a primary precipitate from the magma. Its poikilitic texture in layer type-D appears to be a well preserved igneous texture. The cores with exsolution plates (Plates 16a and 17a) are highly suggestive of a primary hornblende which then grew poikilitically making the texture approach a type of heteradcumulate. If the initial mineral was not hornblende, the original exsolution plates would doubtlessly be annealed. For hornblende to carry exsolution plates means the temperature and pressure must have been at least as high as amphibolite facies conditions. Ross, Papike & Weiblen (1968, p.1100-1101) tried to homogenize tremolite with lamellae at 800°C and 1000 bars PH₂O for 66 days, but their lack of success may have been an activation energy or rate problem. The fact that diopside and hypersthene are found as inclusions in the hornblende though slightly corroded, suggests also a primary hornblende. The graded hornblende layers aid also the argument as do layers such as those of type-B which contain euhedral crystals. Layers of near 100% hornblende from layer type-A (such as those in Plate 5a) display the texture attributed to acccumulate growth (Plate 11b) that is subhedral to anhedral grains (Wager & Brown, 1968, p.64-65, p.318-319).

O'Hara (in Wyllie, 1967, Fig. 1.4) gives a mineral facies diagram for hydrous phases. The amphibole + 2 pyroxene +
plagioclase + olivine facies occurs in the 700° - 900°C and 0 - 30 Kb range. It is cautioned, however, that this is an experimentally based diagram and that the temperature and pressure ranges are only approximate.

A "dry" hornblende of proposed mantle origin is reported by Papike & Clark (1967). The chemical formula given had only half of the amount of water as a normal hornblende from a granitic melt or metamorphic terrain (Deer, et al, 1963, Tables 40 - 43; it should be noted that amphiboles from upper granulite and eclogite facies are also typically "dry"). The occurrence of exsolution lamellae in hornblendes cited in literature is equally from metamorphic as igneous terrains (Klein, 1968).

The magma that formed this layered intrusion probably was intruded prior to or after (not during) the regional metamorphism and first accompanying orogeny. The gravity stratified layers could only form during quiescence of the environment (Wager & Brown, 1968).

The nature of the xenolith at the main, deep outcrop provides a clue as to whether or not the intrusion was metamorphosed or simply displays autometamorphic effects such as in diabase sills. The xenolith is calc-silicate as in the surrounding meta-Wallace country rock. A schistosity paralleling the layering as in the country rocks would indicate regional metamorphism before intrusion since the difference in competence of the ultramafic body would tend
to shield a xenolith from the same type of deformation during regional metamorphism. This suggests the age of the ultramafic body is post-regional metamorphism or post-mid-Mesozoic (~150 m.y.) and pre-Brushy Fork stock, which intrudes the body, or pre-Tertiary (~65 m.y.).

However, evidence is given above (9-10, 16) which indicates prograde metamorphism of the ultramafic body. Actinolite is locally rimmed by hornblende which also contains exsolution lamellae (Deer et al, 1963, p.304-305; Chouduri, 1972). Large plagioclase grains which had been disrupted show recrystallization to smaller grains. This suggests that the age of the body is pre-regional metamorphism or pre-mid-Mesozoic (~150 m.y.) and post-Wallace (~1 b.y.). Further examination of the xenolith and of the intrusion may support either of the two hypotheses.

Convection currents with occasional convective overturn are postulated on the following evidence given previously: rhythmic layers seen in the deep road cut, lineation in one layer decreasing in intensity from bottom up, rhythmic size-graded hornblende layers, nature of the xenolithic inclusion, and zoning in various minerals—particularly, plagioclase and diopside.

A minimum temperature of 1100°C (assuming a pressure of 0.3 Kb) for crystallization conditions of the magma at the stage which these layers were formed can be deduced from the appearance of exsolution lamellae in hypersthene and diopside
(Hess, 1960, p. 35-40). Wager and Brown (1968, p. 338), however, cautioned use of pyroxenes as a geologic thermometer due to scant thermal data.

A geochemical study may reveal cryptic features not found in this study and is highly recommended in future work.

A preliminary gravity survey reconnaissance was run in an attempt to better define the shape of the intrusion. A plot of the Bouguer anomaly revealed no distinct trend and further traverses were abandoned. A slight increase in the negativity of the anomaly was noted on the north edge of the intrusion and is attributed to a part of the Brushy Fork stock outcropping there. This indistinct trend indicates two possibilities: (1) the density of the ultramafic-mafic intrusion isn't greatly different than that of the calc-silicate country rock and (2) the intrusion isn't very deep. The latter possibility could indicate segmentation of a larger layered intrusion by E-W thrust faults which may be common in the area (Nold, 1968). A further detailed gravity survey of the area may reveal these faults and the extent of the mafic ultramafic layered intrusion.

The microscopic and megascopic textures described and discussed in this study point toward an igneous origin for the mafic-ultramafic body south of Lolo Pass. The data are interpreted to demonstrate that the body is a mafic layered intrusion which displays slow cooling and crystal differentiation under the influence of gravity.
Lower layer of sample 14cJ, layer type-A (see Plate 5a). Hornblende (Hb) pseudomorphs an adcumulate texture. Magnetite (Mg) is irregular black patches, some chlorite (Ch) is also present. Foliation and layering is E-W, top is up. (Crossed-nicols)
Sample 54J: Layer type-A with 90% hornblende, almost a complete adcumulate texture. Schistosity of hornblende parallels layering in outcrop. Hornblende (Hb), grays; sphene (Sp) stippled gray with dark edge, no cleavage; magnetite (Mg), black. Chlorite (Ch) laces many of the open areas along the hornblende cleavage planes. The white clear areas are holes, apatite (Ap). Top is up. (Plane light)
Sample (31J) from center of plagioclase-rich layer (layer type-A). The plagioclase laths show a general lamination parallel to the hornblende prisms which parallel the layering in outcrop. Chlorite is replacing hornblende. White, plagioclase (Pl); platy light gray, chlorite (Ch); dark gray, hornblende (Hb); black magnetite (Mg). (Plane light)
Plagioclase (Pl) indicated shows striking resemblance to accumulate plagioclase of the Skaergaard Intrusion (see text, p.16 for reference). Subhedral rims of the plagioclase show a more sodic composition on a euhedral calcic-core. From a plagioclase-rich layer type-A, sample 191bJ. The alteration is sericitic, Hornblende (Hb). (Crossed-nicols)
Breakup of a large plagioclase, with approximate boundary dashed, into smaller grains. Some twins can be traced between several grains. Use of a gypsum plate shows striking optical continuity of this group and a lath-shaped outline, also displayed by many others, two of which are dashed-in on the left side of the picture. Actinolitic-hornblende and chlorite form the finer-grained wedge in the lower left. From sample OJh, layer type-A. (Crossed-nicols)
Severe alteration of plagioclase in spotted-plagioclase hornblende layer (sample 68, layer type-A). White low relief, plagioclase (Pl); white to light gray platy and radial growth, muscovite (Mu); dark gray-platy, chlorite (Ch); almost black, hornblende (Hb), epidote (Ep). Note the tendency of muscovite to good euhedral growth. Hornblende is being altered to chlorite—foliation is E-W, top is up. (Plane light)
Diopside-Hornblende section of layer type-B (sample 33J, Plate 6a). Hornblende (Hb) occurs as large stubby crystals and as alteration of the small diopside (Di) crystals both from within and without. Hornblende contains only a few diopside crystals but is growing acumulately and poikilitically around the subhedral diopside. The lighter pleochroic rim of actinolitic-hornblende can also be seen. (Plane light)
Enlarged view of sample 33J and Plate 13a, showing large hornblendes with slight poikilitic appearance and "ragged" edges. Hornblende (Hb), Diopside (Di). The texture has the appearance of an heteradccumulate (see text for explanation under layer type-B). (Plane light)
Sample 33J as layer type-B with hornblende (Hb) two largest crystals in the picture; diopside (Di) smaller dark gray crystals; plagioclase (Pl), white patch w/ inclusions lower left; quartz (Qz), white patch center bottom. The diopside is highly altered with inclusions of hornblende. The thin white band indicated by the arrow are optically continuous with the larger hornblende, has, however, virtually no pleochroism and therefore shows the sharp break between the hornblende-actinolite families. (Plane light)
Sample OJc of layer type-B from just below center of layer. Plagioclase (Pl) grains are gray, remainder of white interstitial areas are quartz (Qz) (or holes in the slide—upper right corner). Large grains are hornblende (Hb), smaller interstitial & included ones are diopside (Di). Note the lighter pleochroic rims on the hornblende where it contacts and is corroding the diopside. Note also the cores of the two prominent hornblendes as outlined by the mass of inclusions and slightly darker pleochroism. The white inclusion in hornblende at the center right margin is chlorite. Layering is E-W, with top up.

(Plane light)
"Granophyre" within sample 33J layer type-B. The gray to black wedge is strained quartz (Qz), Hornblende (Hb) is the gray to white, euhedral grain in the lower left. Plagioclase (Pl) with some sericitic alteration of calcic cores occupies the remainder of the picture. Note the oscillatory zoning in the plagioclase, which crystallized from the residual melt trapped within this coarse grained layer. (Crossed-nicols)
Another aspect of the residual melts in sample 33J where diffusion was sufficient to grow apatite (Ap). Quartz (Qz) also is present but is not strained, rest of the white areas are holes. Hornblende (Hb) is dark gray with cleavage; sphene (Sp) is almost black and is seen along the hornblende cleavage, possibly exsolved from the hornblende (during metamorphism of titanaugite?). (Plane light)
From sample 119aJ (Plate 7) layer type-C—upper part of a graded layer where hornblende changes from large stubby crystals to acicular ones. The hornblende defines a foliation but not a lineation. Foliation is E-W in picture with top up. Plagioclase (Pl) is poikilitic low-relief white areas with some muscovite (Mu) alteration. Gray areas with inclusions are diopside (Di); euhedral gray crystals of high relief are Hypersthene (Hy), and large gray to black areas with prominent cleavage are hornblende (Hb). (Crossed-nicols)
From sample 119aJ, 1.5 cm. lower in the layer than Plate 15a. Low relief interstitial white areas at top margin are a poikilitic plagioclase (Pl), the rest are holes in the slide. Other interstitial gray areas with vague cleavage are hornblende (Hb). Euhedral to subhedral crystals with inclusion blebs are diopside (Di); the rest are hypersthene (Hy). Black is magnetite (Mg). The foliation is E-W with top up. (Plane light)
From sample 119b just above concentration of large hornblendes (see Plate 7). A large hornblende (Hb) poikilocryst is at far right edge of the picture. The most prominent feature is the large zoned diopside (Di) crystal which is twinned. The zoning is not compositional perse but is observed in the concentration of hypersthene exsolution lamellae around a core choked with lamellae. (Other diopside (Di) crystals contain blebs of hornblende.) Exsolution lamellae of clinopyroxene are seen in the elongate hypersthene (Hy). Poikilitic plagioclase is also indicated. The layering is E-W with top up. (Crossed-nicols)
Sample 57J from main outcrop on U.S. 12. A type-C layer similar to bottom of sample 119J (Plate 7) but with less diopside. A hypersthene-rich layer with extensive poikilitic plagioclase (Pl), the large hornblende (Hb) crystal shows a core free of inclusions but with possible exsolution platelets and has grown poikilitically into the hypersthene (Hy). Alteration of hypersthene to hornblende is concentrated around the large hornblende. Magnetite (Mg) is black. The "X" refers to the same in plate 16b. The poikilitic plagioclase is optically continuous throughout both photographs and extends beyond to a total size approximately 5 x 7 mm. A few diopside (Di) grains contain hornblende blebs. Top is up. (Plane light)
Sample 119bJ at bottom of graded layer (Plate 7). The large hornblende (Hb) with a simple twin has a core which contains inclusions suggestive of exsolution lamellae. This core is accentuated by poikilitic growth of the hornblende into the hypersthene (Hy) and Diopside (Di). Diopside contains the most abundant hornblende blebs. Layering is E–W with top up. (Crossed-nicols)
Lower poikilitic hornblende (Hb) is same grain as in Plate 17a which is 5 mm. to the left. A second poikilitic hornblende in extinction has grown and met the first; note the wavy border between the two. Diopside (D1) is most altered gray grains, Hypersthene (Hy) the less altered. Note faintly zoned hypersthene below and left of center. Foliation is E-W with top up. (Crossed-nicols)
A large plagioclase in sample #OJP (layer type-D) shows a carlsbad twin of igneous origin with albite and pericline twins of probable metamorphic origin. Larger white albite twins are igneous in origin. Note the zonation of twins and inclusions within the plagioclase. The dark gray background is a single poikilitic hornblende; the smaller crystals are hypersthene. (Crossed-nicols)
"Inter-poikilitic" area in sample #OJP (layer type-D) showing typical internal replacement of diopside by hornblende. Most of the poikilitic hornblende is optically continuous, that within the diopside is internally continuous only. The indicated plagioclase (Pl) has a less calcic rim possibly due to loss of calcium to hornblende formation. Hypersthene appears little altered internally. Black magnetite (Mg); dark gray hornblende (Hb); gray diopside (Di) and hypersthene (Hy); and white, plagioclase (Pl). (Plane light)
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