PETROGENESIS OF THE LAWSON PEAK ORBICULAR GABBRO

A Thesis
Presented to the
Faculty of
San Diego State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
in
Geology

by
David Russell Hoffman
May 1975
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Approved by:

[Signatures and dates]
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Chapter 1

INTRODUCTION

The Lawson Peak gabbro outcrops in an area twenty-five miles east of San Diego, near Barrett Reservoir in San Diego County, California. The gabbro covers an area of approximately 4.5 to 5 square miles and consists of scattered, bouldery outcrops produced by chemical weathering along joints and fractures. The semiarid climatic conditions in the region have produced a thick soil horizon and dense vegetation which, combined with deep chemical weathering, makes direct observation of contacts between the various rock units difficult. The rock units in the area include tonalite of the Bonsall type, granodiorite of the Woodson Mountain type, gabbro (here termed the Lawson Peak gabbro), and a variety of felsic and pegmatite veins and dikes. Field relations indicate that the tonalite is intrusive into the gabbro, and the granodiorite is intrusive into both gabbro and tonalite.

The Lawson Peak gabbro is a combination of gabbroic and ultrabasic phases including hornblende
gabbro (the most abundant phase), olivine gabbro, pyroxene-hornblende gabbronorite, peridotite, anorthositic gabbro, and anorthosite. The main hornblende gabbro phase has a fairly uniform grain size and texture, but the gabbronorite has both a fine- and medium-grained phase, discontinuous layered units, and an orbicular phase. The orbicular gabbronorite is restricted to several small lensiodal bodies which contain a dense population of orbicules in a matrix of medium-grained pyroxene-hornblende gabbronorite.

Previous work in this area has been confined largely to studies of the felsic rocks of the batholith, with little attention to the gabbroic rocks. The most extensive studies of the prebatholithic plutonics (gabbros, mainly) are those of Hanna (1926), Creasey (1946), W. J. Miller (1946), and Larsen (1948). Some work has been done on the Jurassic metavolcanics of the area by Fife and others (1967). Other recent work on the Peninsular Ranges batholith has concentrated mainly on the tectonics, regional petrochemistry, and geochronology (Bushee and others, 1963; Banks and Silver, 1968; Evernden and Kistler, 1970; Armstrong and Suppe, 1973). Studies of the gabbroic rocks are limited (F. S. Miller, 1937, 1938), as is detailed recent work on the orbicular rocks of this area
(Kessler, 1904; Lawson, 1904; Schaller, 1911; Merriam, 1948, 1958). Detailed work on orbicular rocks of other areas is also limited, the most extensive being those of Johnston (1936), Eskola (1938), Howard (1940), Campbell (1942), Goodspeed (1942, 1948), Carl and Amstutz (1958), Emerson (1963), Leveson (1963, 1966), Moore and Lockwood (1970, 1973), Van Diver (1970), and Thompson and Giles (1974).

The purpose of this study was to produce a detailed field map (at a scale of 1:24,000) of the area surrounding the Lawson Peak pluton showing not only the distribution of major rock types, but also the various phases of the Lawson Peak gabbro (Plate I in back pocket). Then these data were combined with complete petrographic analyses of the various rock units of the Lawson Peak pluton to reconstruct the petrogenetic history of the pluton and its associated structures.

The majority of the field mapping was carried out during the summer of 1974. Forty thin-sections of representative rock samples were prepared and studied. The locations of these samples are shown on Plate II (see back pocket) and the rock names and mineralogical modes are included in the appendix. Rock names were assigned using the International
Union of Geological Sciences (I.U.G.S.) system of classification. Mineral compositions based on optical data are taken from Poldervaart (1950), Kerr (1959), and Deer and others (1971).

Many of the features of the Lawson Peak pluton are analogous with features of layered intrusions. For this reason, much of the terminology contained in this paper is taken from the classic works on large layered intrusions such as the Stillwater and Skaergaard complexes. For a complete definition of terminology, the reader is referred to one of the following works: Hall (1932), Wager and Deer (1939), Poldervaart and Taubeneck (1958, 1960), Hess (1960), Taubeneck and Poldervaart (1960), Wager and others (1960), and Wager and Brown (1968).
Chapter 2

ABSOLUTE AGE DATING

A sample of typical medium-grained hornblende gabbro (sample number DRH 7-74-17) was analyzed by the potassium-argon method to determine the minimum cooling age for this phase of the Lawson Peak gabbro. The sample was thin-sectioned to determine the freshness of the rock, then crushed, pulverized and sieved to 200-mesh. After removing the magnetic fraction of the sample, a Franz magnetic separator was used to separate the plagioclase from mafic phases. An amphibole separate was obtained by floatation in diiodomethane. Final samples for both plagioclase and amphibole were hand-separated and cleaned under the microscope to obtain maximum sample purity. Potassium and argon extraction and measurement was performed at the San Diego State University radiometric dating laboratory, and the final age determination was made by Dr. Daniel Krummenacher. Results of this analysis are tabulated on Table 1.

These dates, of course, represent age of closure to loss of argon; that is, the approximate
Table 1
Potassium-Argon Age Dating Sample DRH 7-74-17

<table>
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<tr>
<th>Mineral</th>
<th>Potassium</th>
<th>Radiogenic Argon</th>
<th>Age (M.Y.B.P.)</th>
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<tr>
<td>Amphibole</td>
<td>0.184%</td>
<td>12.27%</td>
<td>129.1 ± 18.6</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>0.292%</td>
<td>39.86%</td>
<td>99.6 ± 3.1</td>
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cooling age of this phase of the pluton. The dates are concordant with dates on the same minerals in other gabbroic rocks of the Peninsular Ranges batholith although somewhat older. The lowermost Cretaceous age (on amphibole) for this pluton and a date of 143 MYBP for the Los Pinos gabbro (R. G. Gastil, oral communication, 1975) are among the oldest dated rocks in the Peninsular Ranges batholith.

Lead-alpha ages (on zircon and monazite) reported for granodiorite of the Woodson Mountain type average 110 MYBP, and for tonalite of the Bonsall type average 120 MYBP (Bushee and others, 1963). Both these ages are for rocks found in the Ramona, Bonsall, and Cuyamaca quadrangles. The felsic rocks in this area are essentially the same as in those quadrangles and thus are probably similar.

Radiometric age dating, therefore, supports the observed field relationships. In both cases the gabbroic rocks are the oldest and the felsic rocks are younger.
Chapter 3

FELSIC ROCK UNITS

TONALITE

Tonalite in the study area intrudes the Lawson Peak gabbro and is in turn intruded by granodiorite. It consists of coarse- to medium-grained tonalite and quartz diorite. In outcrop, these rocks weather easily, forming characteristic bouldery outcrops. The most characteristic feature of this unit are the widely distributed, abundant diorite-like inclusions and schlieren zones. Inclusions and schlieren zones are most abundant adjacent to the gabbro body, but some are found scattered sparsely throughout the tonalite. When adjacent to the gabbro, inclusions are aligned parallel or subparallel to the gabbro-tonalite contact. Further from the gabbro, inclusions show no preferred orientation.

Petrographically, rocks of this unit contain quartz, plagioclase, amphibole, biotite, and minor opaques. In all cases, plagioclase shows strong normal zoning with a slightly resorbed core. The composition of the plagioclase is variable with the core generally
in the high andesine to low labradorite range, whereas the rim is generally in the range of oligoclase. Amphibole shows green to dark green pleochroism typical of common hornblende and most amphibole appears to have formed at the expense of pyroxene which now occurs as minor relict cores in amphibole. Biotite is found throughout these rocks, up to 20 modal percent in some cases and appears to have formed at the expense of amphibole.

The outcrop expression, abundant dioritic inclusions and schlieren zones, and mineralogy of this unit are similar to Bonsall tonalite described by Larsen (1948). Such correlations, however, are beyond the scope of this paper so that this unit will be referred to as tonalite of the Bonsall type.

GRANODIORITE

Granodiorite in the study area is intrusive into both gabbro and tonalite. It consists of light-colored, medium- to fine-grained biotite-hornblende granodiorite and tonalite. In outcrop this unit is quite resistant to weathering, forming the two most prominent peaks in the area, Lawson Peak and Gaskill Peak. The rock itself is generally homogenous. Multiple joint sets and deep chemical weathering have
produced blocky outcrops.

Petrographically, the granodiorite contains alkali feldspar, plagioclase feldspar, quartz, amphibole, biotite, and minor opaque material. Plagioclase is generally strongly zoned, composition ranging from high andesine to oligoclase in most cases. Alkali feldspar is found throughout the unit, and comprises up to 20 percent of the total feldspar. As in the tonalite, amphibole (again common hornblende) has formed at the expense of pyroxene, and biotite has formed at the expense of amphibole.

Although very few mafic inclusions are found in this unit, there are some zones of extensive schlieren. Those bordering the gabbro are aligned parallel to the contact. The outcrop characteristics and mineralogy of this unit are similar to rocks of the Woodson Mountain granodiorite described by Larsen (1948). As with the tonalite, correlations such as this are beyond the scope of this paper and this unit will be referred to as granodiorite of the Woodson Mountain type.

**FELSIC VEINS AND DIKES**

Abundant pegmatite dikes and veins, quartz veins, and other felsic intrusions of minor extent are
found scattered throughout the area. These are particularly noticeable in the Lawson Peak gabbro due to contrasting outcrop colors. As these rocks are probably related to the granodiorite and/or tonalite, they will not be considered here in any detail.

Typical modes and rock nomenclature for rocks of the two felsic units are given in the appendix.
The Lawson Peak gabbro forms a topographic low relative to the surrounding felsic rock units. The pluton is surrounded by granodiorite on the north and west margins, and by tonalite on the south and east margins. The majority of the southern contact between the gabbro and tonalite is covered by alluvial deposits in the small valley in the central portion of the area. Contacts between the gabbro and felsic rocks are nearly vertical in all observable instances, but seem to dip slightly inward on the north and outward on the west margin of the pluton. The distribution of the major rock types in the area is shown on Plate I (see back pocket). The gabbro itself consists of dark, bouldery outcrops, distinctly darker and less well-exposed than either of the two felsic units. A thick soil zone, reddish in color for the most part, is developed in all areas of the pluton. Color of the soil depends entirely on rock type; the olivine gabbro phase has a much darker red color than the rest of the pluton, the
peridotite phase has soil coverings of a distinct greenish color, and anorthosites and anorthositic gabbros have soil zones of a neutral gray or other light color. A thick cover of vegetation is found throughout the study area and consists of various forms of perennial plants typical of this semiarid environment.

The dominant rock type in the Lawson Peak pluton is a medium-grained hornblende gabbro. Other rock types found in the pluton include olivine gabbro, pyroxene-hornblende gabbronorite, peridotite, anorthosite and anorthositic gabbro. The mafic-rich phases are distributed throughout the main hornblende gabbro phase. Contacts between the various phases are not well exposed, and most contacts are located as closely as possible by using topographic and vegetation/soil changes as well as outcrop characteristics. Field evidence indicates that many of the phases of the Lawson Peak pluton are gradational into one another. More specifically, olivine gabbro is gradational into peridotite and anorthosite is gradational into anorthositic gabbro (leucogabbro). The fact that many contacts are gradational makes locating boundaries between these phases difficult.

In the following section each of the individual
phases of the pluton will be treated separately, and the overall petrographic characteristics will be summarized at the end of this chapter. The orbicular phase of the pluton will be considered separately and in more detail in a later chapter.

MAJOR ROCK TYPES

Hornblende Gabbro

Hornblende gabbro has the largest surface extent of all the phases present in the Lawson Peak gabbro. In outcrop, this phase is dark, bouldery, and cut by multiple joint sets and fractures. Outcrop surfaces are fairly fresh in most cases. The hornblende gabbro is texturally and modally variable. In hand specimen, it can be broken down into three basic groups: hornblende gabbro, layered gabbro, and orbicular gabbro. The layered units of this phase will be considered as a separate section of this chapter, whereas the orbicular rocks will be considered in detail in a later chapter.

From petrographic study of this phase, two basic groups can be distinguished. The first is compositionally a pyroxene-hornblende gabbronorite consisting of four phases: fine-grained, medium-grained, pegmatitic, and a "spotted" or poikilitic
phase. The second group is compositionally a hornblende gabbro and is texturally and modally constant (relative to the gabbronorite).

1. Pyroxene-hornblende gabbronorite.
   a. Fine-grained pyroxene-hornblende gabbronorite. In the field, fine-grained gabbronorite is associated with and intruded by the medium-grained gabbronorite. In hand specimen, however, they both are difficult to distinguish from hornblende gabbro. This phase typically contains plagioclase, amphibole and pyroxene.

   Plagioclase generally occurs in two size populations. The first of these is much larger with subhedral equant grains. Most have border and internal resorption features, strong zoning and filling of resorption holes with pyroxene and plagioclase. The large crystals have some well-developed albite twins while others show no twinning. Larger grains also show normal and oscillatory zoning ranging from a maximum anorthite content of $\text{An}_{75}$ to $\text{An}_{78}$ in the cores to an approximate minimum of $\text{An}_{60}$ on rims. Surrounding these large grains is a smaller population of crystals, most anhedral and interlocking, poorly twinned, slightly zoned, with a compositional average of about $\text{An}_{52}$ to
Amphibole occurs both as interstitial (intercumulus) patches in spaces between lath-like, framework plagioclase crystals and as alteration coronas formed at the expense of pyroxene. This amphibole has high relief, typical amphibole cross-section, pleochroism from almost colorless to pale shades of green and brown, extinction \((\gamma\Delta C)\) inclined about \(20^\circ\) to \(23^\circ\), first-order yellow interference color and a positive axial angle (moderate \(2V\)). The composition of this amphibole based on optics is edenitic.

Pyroxene occurs as small, rounded subhedral grains, most more or less altered to amphibole. Some grains are enclosed poikilitically by large plagioclase laths and are not noticeably altered to amphibole. Optically this pyroxene has parallel extinction, first-order gray interference color, axial angle \((2V)\) near \(80^\circ\), negative optic signs and pleochroism from pale green to pale pink. The composition based on optics is in the range of hypersthene.

b. Medium-grained pyroxene-hornblende gabbronorite. This phase typically contains plagioclase, amphibole and pyroxene. It is similar mineralogically to the fine-grained gabbronorite.

Plagioclase in this phase occurs as
large euhedral to subhedral, equant to subequant crystals, with well-developed albite-carlsbad twinning and no zoning or resorption. The grains form a tight, cumulus network with interstices filled by smaller plagioclase and amphibole grains. The composition of the larger grains is $\text{An}_{76}$ whereas that of the smaller crystals appears to be about $\text{An}_{70}$ to $\text{An}_{74}$. Most contain minor zircon and apatite inclusions.

Amphibole forms an intercumulus network between the framework of cumulus plagioclase grains. Optically it has high relief, pleochroism from nearly colorless to pale shades of brown and green, typical amphibole cross-section, first-order yellow interference color, extinction inclined $20^\circ$ to $25^\circ$ and a positive optic sign. The composition of this amphibole is edenitic, based on optical data. Much of the amphibole in this phase appears to have formed at the expense of pyroxene.

Pyroxene is usually found as relict crystals in the centers of masses of amphibole, whereas some grains are found associated with vermicular patches of opaque material. Optically it has high relief, pleochroism from pale pink to pale green, parallel extinction, first-order gray interference color, high negative $2V$, and some poorly developed exsolution
lamellae. Composition of this pyroxene is in the range of hypersthene.

Textural differences between the fine-grained and medium-grained phases of the pyroxene-hornblende gabbronorite can best be illustrated by Figures 1 and 2.

c. Pegmatitic pyroxene-hornblende gabbronorite. In outcrop the pegmatitic phase of this unit occurs as small irregular masses and vein-like bodies in otherwise homogenous medium-grained hornblende gabbro (Figure 3). These masses contain plagioclase, olivine, amphibole and pyroxene.

The plagioclase occurs as large, cumulus, subequant and anhedral grains with complex albite-carlsbad-pericline twinning, no zoning or resorption and a compositional maximum of An\textsubscript{68}. These large grains form a framework surrounding the other interstitial minerals (olivine, orthopyroxene and amphibole). Smaller grains have the same physical and optical properties and appear to have the same composition.

Olivine occurs as scattered, highly altered (to magnetite, serpentine and/or iddingsite) and fractured, rounded and resorbed subhedral grains. A high positive axial angle (2V = 85°) indicates that
Figure 1. Photomicrograph (Plane Polarized Light) of Sample DRH 8-74-10A, Showing Texture and Mineralogy of Fine-Grained Gabbronorite (Opx = Orthopyroxene; Plag = Plagioclase; Amph = Amphibole; Opq = Opaque)

Figure 2. Photomicrograph (Plane Polarized Light) of Sample DRH 8-74-10B, Showing Texture and Mineralogy of Medium-Grained Gabbronorite (Abbreviations Same as in Figure 1)
Figure 3. Outcrop of Hornblende Gabbro Showing Coarse-Grained (Pegmatitic) Segregation of Gabbronorite
the composition is about Fo$_{90}$.

Amphibole has high relief, pleochroism from colorless to pale green and brown, positive optic sign, first-order yellow interference color and an extinction angle ($\gamma\Delta C$) of 12° to 15°. Most amphibole appears to have formed at the expense of pyroxene.

Pyroxene is generally found filling interstices between the plagioclase-crystal network. Optically it has high relief, faint pleochroism, extinction inclined 43° to 45°, second-order blue interference color, positive axial angle (2V) of 10° to 15° and two cleavages at 90° with some indistinct exsolution lamellae parallel to one cleavage direction. On the basis of optical properties, the composition of this pyroxene is probably pigeonite. Some grains poikilitically enclose plagioclase. In most cases, a reaction rim of amphibole surrounds the pyroxene grains even when in contact with poikilitically enclosed plagioclase.

d. Poikilitic pyroxene-hornblende gabbro-norite. "Spotted" gabbros are found in several places in the pluton, their most striking feature being the large poikilitic pyroxene crystals, some up to 10 cm across. Mineralogically these rocks consist of
plagioclase, amphibole, olivine and two pyroxenes.

The plagioclase occurs in two size populations. The first population consists of large equant subhedral grains with strong resorption effects and complex twinning. The approximate composition of this population is An$_{70}$. Crystals of the second size population are small, anhedral and poikilitically enclosed by amphibole and pyroxene. The composition of the smaller grains (which show much simpler forms of twinning) is not possible to determine accurately by optical methods.

Olivine occurs as rounded, resorbed subhedral grains, highly fractured and altered to magnetite, serpentine and/or iddingsite. Many of the larger grains of olivine are surrounded by a mantle of hypersthene (see below). There are several areas that have an olivine outline but consist of hypersthene in an irregular vermicular intergrowth with opaque material. These patches may be pseudomorphic after olivine.

Orthopyroxene has high relief, a negative axial angle of 80° to 85°, some schiller lamellae, parallel extinction and pleochroism from pale green to pale pink. On the basis of optical properties, the composition is in the range of hypersthene. Orthopyroxene occurs both as individual grains (usually
associated with olivine and/or opaques or as large, poikilitic crystals enclosing plagioclase and olivine. These large crystals give the rock its "spotted" texture in the outcrop.

Clinopyroxene has high relief, simple twins with a single twin plane, a positive axial angle of 5° to 10°, second order red interference color and no distinct pleochroism. Based on optical properties the composition of this pyroxene is pigeonite. Clinopyroxene occurs as large euhedral crystals and as smaller grains enclosed poikilitically by amphibole. Some orthopyroxene in this phase has optical properties (such as low axial angle and simple twinning) similar to the clinopyroxene. These crystals are probably inverted pigeonite.

Amphibole generally occurs as large, poikilitic crystals enclosing olivine and plagioclase and appears to have formed at the expense of pyroxene. This amphibole has the same colorless to pale green and brown pleochroism and positive optic sign as the other amphiboles in the gabbronorite and is probably edenitic in composition.

2. Hornblende gabbro.

a. In outcrop, the texture of this unit is in distinct contrast to the texturally variable
pyroxene-hornblende gabbronorite. It is homogenous in grain size, texture, and mineralogy. In most cases, it is practically impossible to distinguish this unit from the medium-grained phase of the gabbronorite in the field, which is why all phases of the gabbronorite (with the exception of the orbicular phase) are mapped with hornblende gabbro as a single unit. Petrographically hornblende gabbro consists mainly of plagioclase and amphibole.

In all cases plagioclase forms an interlocking network of cumulus crystals, usually elongated laths with well-developed carlsbad twinning (albite twinning is poorly developed). Most crystals have a resorbed calcic core with an anorthite content of An$_{80}$ to An$_{82}$. A compositional break exists between the core and surrounding rim. This later growth of plagioclase fills most of the interstitial space between adjacent laths. The surrounding rim is normally zoned with compositions ranging from An$_{55}$ in the innermost zone next to the core to about An$_{35}$ in the outermost zone of the rim. Final growth of most of the plagioclase crystals preceeded growth of intercumulus amphibole. Some plagioclase is poikilitically enclosed by amphibole. These show no additional
growth beyond the core which has an anorthite content of \( \text{An}_{70} \) to \( \text{An}_{72} \). Calcic cores show alteration to epidote-group minerals and minor calcite.

Amphibole occurs both as large poikilitic crystals enclosing euhedral laths of calcic plagioclase (as described above) and as separate crystals interstitial to the interlocking plagioclase crystals. Optically this amphibole has high relief, pleochroism from pale green and brown to light green and brown, extinction inclined \( 20^\circ \) to \( 25^\circ \), amphibole cleavage, moderate negative axial angle, and first-order yellow interference color. The darker pleochroism (relative to the gabbronorite) and negative axial angle found in this amphibole indicates a composition closer to common hornblende.

Although present in minor amounts in this unit, pyroxene occurs mainly as relict grains in the centers of amphibole crystals. The only optical data available on this pyroxene is the second order red interference color and inclined extinction (\( 40^\circ-45^\circ \)) which indicates that it is a clinopyroxene.

At one location in the main hornblende gabbro phase of the pluton (20 meters north of sample locality DRH 7-74-17) are found several small lensoidal bodies rich in iron-oxides. X-ray diffraction of the
material in these segregations shows it to be a complex mixture of magnetite (mainly) hematite, and pyroxene.

**Olivine Gabbro**

Although in outcrop and field expression a distinct mappable unit, the olivine gabbro phase of the Lawson Peak gabbro shows considerable variations in mineralogy. The mineral with the most variable modal percentage in this phase is olivine, which ranges from 0 to 35 modal percent. In those rocks containing olivine, it occurs as rounded, subhedral grains with a certain degree of resorption and embayment. The grains are generally highly fractured with alteration to serpentine, magnetite and iddingsite along these fractures. In most rocks containing olivine, the olivine grains are poikilitically enclosed by amphibole. Some phases of this unit do not contain any primary olivine crystals but instead have a complex vermicular intergrowth of orthopyroxene and opaque material. In these rocks, such as DRH 2-75-5, areas of vermicular opaques and orthopyroxene appear to be pseudomorphic after olivine. In the same rock, fresh olivine grains can be found but in all cases these fresh grains are mantled by intercumulus amphibole.

In sample DRH 7-74-11, rounded, resorbed, and
embayed olivine crystals are found in direct contact with plagioclase (in other samples of this unit, the olivine is mantled by intercumulus amphibole). In this case there is a zone between the olivine crystal and the surrounding plagioclase. This zone consists of a vermicular intergrowth of greenish spinel (pleonaste?) on the plagioclase side of the interface between the two minerals and what appears to be orthopyroxene (high relief, parallel extinction, first-order yellow interference color and a negative axial angle of 80°) on the olivine side (Figures 4 and 5). Optical data on this zone is difficult to obtain due to the small size and complexly intergrown nature of the two minerals.

Amphibole in the olivine gabbro unit appears optically to be remarkably consistent in composition and textural relations with the other minerals. Optically it has typical amphibole cross-section, high relief, low first-order yellow interference color, pleochroism from near colorless to pale brown and green and a moderate axial angle (positive). On the basis of optical properties, the composition of this amphibole is edenitic. Texturally the amphibole is always interstitial, and when present in large amounts
Figure 4. Photomicrograph (Plane Polarized Light) of Sample DRH 7-74-11, Showing Olivine Crystals (Ol) Bordered by Reaction Rim of Orthopyroxene (?) (Opx) and Pleonaste Spinel (Sp). Other abbreviations as in Figure 1, page 19.

Figure 5. Same as Figure 4, Showing Detail of Olivine Reaction Rim
it poikilitically encloses plagioclase, olivine, and pyroxene (all three are not necessarily present in the same slide). In samples containing abundant pyroxene, much of the amphibole appears to have formed at the expense of pyroxene.

The dominant pyroxene in the olivine gabbro unit is orthopyroxene. Minor amounts of clinopyroxene (mostly augitic) are present and have the same textural features as the orthopyroxene. Orthopyroxene has high relief, first-order gray-yellow interference color, generally parallel extinction, pleochroism from pale pink to pale green, negative axial angle (2V) of 85° and, in most crystals, a certain amount of exsolution lamellae of clinopyroxene (diopsidic?) is developed. Pyroxene shows three different stages of reaction with the melt; first are those with resorbed and altered olivine at the cores of pyroxene crystals, second are those pyroxenes which are resorbed and altered to amphibole, and third are those individuals which show neither of the reactions with olivine or amphibole. This third group is found as a vermicular intergrowth with opaque material, particularly in sample DRH 8-74-11. This intergrowth forms the rough outline of a relict olivine crystal.

Plagioclase in this unit is variable both in
textural relations with other minerals and in composition. In those samples containing abundant olivine, plagioclase is interstitial and unzoned with a composition around An\textsubscript{70} to An\textsubscript{74}. In those samples with vermicular intergrowths of opaque material and orthopyroxene, the plagioclase forms an interlocking network of large, lath-like crystals with normal zoning from An\textsubscript{72} to An\textsubscript{62}. For the most part, however, plagioclase in this unit is unzoned with compositions ranging up to a maximum of An\textsubscript{84} and averaging An\textsubscript{74}. Plagioclase forms a network of complexly twinned crystals (combined carlsbad-albite-pericline), with olivine, pyroxene, and amphibole filling the interstices between plagioclase crystals.

Anorthosite and Anorthositic Gabbro

The anorthositic phase of the Lawson Peak pluton ranges from leuco-hornblende gabbro to anorthosite in composition. These rocks contain 68% to 94% plagioclase with amphibole making up the remainder of the rock. Some relict pyroxene is present in minor amounts (1% to 2%). Rhythmic layering is found in some outcrops of this unit (Figure 6).

Plagioclase is generally calcic with anorthite contents between An\textsubscript{85} and An\textsubscript{90}. Zoning and resorption
Figure 6. Outcrops of Layered Anorthositic Gabbro. Scale is 50 cm.
are absent in these rocks and the plagioclase crystals form an interlocking cumulus framework of large, equant grains. Although zoning is essentially absent, most grains have a thin rim of slightly lower anorthite content (usually around $\text{An}_{74}$ to $\text{An}_{80}$). Twinning is usually a complex combination of carlsbad, albite, and pericline types.

Amphibole percentage is variable from 4% to 28% but is fairly constant in optical properties throughout. It forms an interstitial, intercumulus phase (Figure 7), in some cases having formed at the expense of pyroxene and in others altered to chlorite. In the one anorthosite sample (DRH 9-74-2), accessory zircon contained in the amphibole has distinct pleochroic halos. Optically the amphibole has high relief, typical amphibole cross-section, first-order yellow interference color, moderate (positive) axial angle, pleochroism from pale yellow-green to pale brown with extinction inclined $15^\circ$ to $20^\circ$. On the basis of optical properties, the amphibole composition is edenitic.

Textural features in this phase are straightforward with the plagioclase forming an interlocking cumulus framework, and the amphibole filling interstices within this framework.
Figure 7. Photomicrograph (Plane Polarized Light) of Sample DRH 9-74-2 (Anorthosite) Showing Intercumulus Amphibole (Amph) with a Relict Pyroxene Core (Cpx) Surrounded by Cumulus Plagioclase (Plag)
Peridotite

Rocks of the peridotite phase of the Lawson Peak gabbro range in composition from olivine-pyroxene hornblendite to pyroxene-hornblende peridotite and spinel-hornblende peridotite. In all rocks studied, olivine and plagioclase form the cumulus network of interlocking crystals, which are usually more or less poikilitically contained by amphibole and/or pyroxene.

Olivine in the peridotite phase of the Lawson Peak gabbro occurs as subhedral, subequant grains. All olivine crystals do show extensive fracturing and late-stage deuteritic release of magnetite and alteration to serpentine along fractures. When olivine is in close proximity to plagioclase (some in direct contact), there is generally a border zone of an opaque phase (magnetite?) and amphibole. The border zone in this case is not the same as that found in the olivine gabbro. It appears that these opaques are being released by breakdown of the olivine. In all cases, olivine is more or less poikilitically enclosed by amphibole and/or pyroxene.

Plagioclase in the peridotite phase occurs as two texturally distinct populations. The first exhibits the same textural features as olivine, that is, subequant grains enclosed poikilitically by amphibole
and/or pyroxene. Unlike the olivine, however, these plagioclase grains do show considerable embayment and resorption with resorbed patches filled by amphibole and plagioclase. The second group of plagioclase crystals occur as small, subhedral to anhedral grains associated with interstitial patches of amphibole and in resorbed patches in plagioclase of the first group. Composition of the first group (cumulus, resorbed crystals) ranges from $\text{An}_{80}$ to $\text{An}_{88}$, whereas the composition of the smaller, interstitial crystals (although difficult to determine optically) appears to average around $\text{An}_{70}$ to $\text{An}_{72}$.

Pyroxene in the peridotite phase shows the same textural relations as olivine in that it occurs as small, subhedral grains poikilitically enclosed by amphibole. As in the cumulus plagioclase grains, the pyroxenites generally are somewhat rounded, resorbed, and embayed. Some rocks contain an orthopyroxene (with parallel extinction, pale pink to pale green pleochroism, slight schiller exsolution lamellae, and high axial angle) in the compositional range of hypersthene, while others contain a clinopyroxene (nonpleochroic, second-order red interference color, extinction inclined about $40^\circ$), probably of augitic composition. In no rocks, however, were both a clino- and orthopyroxene
found together. In all cases the pyroxene phase shows alteration to amphibole.

Amphibole in this phase has high relief, pleochroism from pale green and brown to nearly colorless, first-order yellow interference color, moderate (positive) axial angle and inclined extinction (20° to 25°). Based on optical properties, the composition is edenitic. Texturally the amphibole poikilitically encloses olivine, plagioclase and pyroxene (all three are not necessarily present in the same slide), and in many cases having formed at the expense of pyroxene.

Translucent green spinel of pleonaste composition is found in abundance in rocks of this phase, in some cases making up 8 modal percent (DRH 9-74-1).

**LAYERED GABBRO**

Layering is found in several scattered locations in the main phase of the amphibole gabbro and is usually closely associated with the gabbronorite phases. This is rhythmic-type layering, consisting for the most part of alternating mafic-rich and plagioclase-rich layers. The layering is similar to that found in the anorthosite except that it is not as extensive either laterally or vertically, and features such as graded bedding are better developed in the layered gabbro.
Unfortunately, sections of layered gabbro are so discontinuous, both laterally and vertically, so few in number, and so widely distributed that no useful orientation data can be obtained. In addition, many of the outcrops of layered gabbro do not appear to be in place, again making orientation measurements useless.

Thin-section study of layered gabbro shows that the leucocratic layers are made up almost entirely of plagioclase. The layers consist of mostly equant grains of plagioclase which form a tight, interlocking framework of cumulus grains. Grain boundaries between plagioclase crystals are almost exclusively at 120°. Plagioclase is not zoned or resorbed and few grains show any well-developed twinning. Composition of most of the crystals is between An$_{80}$ and An$_{85}$. Minor intercumulus (interstitial) material consists of a clinopyroxene which is surrounded by and more or less altered to an amphibole showing colorless to pale green pleochroism. The clinopyroxene is colorless and non-pleochroic in plane light; under crossed nicols, it shows low second-order interference colors, simple twinning (with a single twin plane), inclined extinction and a positive axial angle of about 10° to 15°. These
optical data and the presence of exsolution lamellae suggest that this is an inverted pigeonite.

Dominant mineral phases of the melanocratic layers are plagioclase, pyroxene, and amphibole. Plagioclase occurs as large, equant grains which form the cumulus network. A smaller population of plagioclase is poikilitically enclosed by both pyroxene and amphibole. Composition of the large population is consistent with that of the leucocratic layers and grains of the small population are too small to make any accurate determination of composition. Clinopyroxene is present with the same optical properties as in the leucocratic layers and, on the basis of those properties, is also probably a pigeonite or inverted pigeonite. The cumulus clinopyroxene grains are surrounded by an intercumulus orthopyroxene. This later-stage pyroxene is colorless and nonpleochroic in plane light, and under crossed nicols has a first-order gray interference color, parallel extinction, well-developed schiller lamellae, and negative axial angle of 80° to 85° (probably in the compositional range of bronzite to hypersthene). Both these pyroxenes are in turn surrounded by and more or less altered to a light-colored amphibole with colorless to pale green
pleochroism which is the final intercumulus material. Composition of this amphibole is probably edenitic. Olivine is present in the melanocratic layers in small amounts, particularly near the contact with the leucocratic layers. Further from the leucocratic layers no olivine is found but, instead, vermicular intergrowths of opaque material and orthopyroxene identical to those commin in some of the olivine gabbros are found. These intergrowths could represent relict olivine crystals removed from the system by some reaction which produces opaques and orthopyroxene at the expense of olivine.

The bulk mineralogy of the layered gabbro indicates that it is closer in composition to the gabbronorite phase than the hornblende gabbro phase.

SUMMARY OF PETROGRAPHIC DATA

The major petrographic features of the various phases of the Lawson Peak gabbro can be summarized as follows:

1. In all the phases olivine (when present) and plagioclase are the cumulus minerals, and were therefore on the liquidus during crystallization of
the magma. The nearly simultaneous crystallization of these two minerals is also indicated by the reaction coronas around olivine when it is in contact with plagioclase.

2. The intercumulus phase in all the rocks of this pluton is amphibole. On the basis of optical properties, the composition of this amphibole is Ca-hornblende, probably in the range of edenite in almost all cases. The composition of amphibole in hornblende gabbro, however, is probably closer to common hornblende. Much of the intercumulus amphibole appears to have formed at the expense of pyroxene.

3. Pyroxenes in the Lawson Peak pluton include both an orthopyroxene of bronzite to hypersthenic composition and a clinopyroxene of pigeonite composition.

4. Plagioclase in the differentiates (olivine gabbro, anorthosite, peridotite) is unzoned and unresorbed with a composition in the range of bytownite. The plagioclase in the main hornblende gabbro phase has resorbed calcic cores surrounded by a zoned rim with compositions of labradorite-bytownite to andesine.

5. Layering in rocks of the Lawson Peak gabbro have a distinct cumulate texture in both leucocratic and
melanocratic layers. Layering is the result of gravitative differentiation and crystal settling.

6. Rocks of the pyroxene-hornblende gabbro-norite phase show the widest textural variations and include both a fine-grained and medium-grained phase, a "spotted" (poikilitic) phase, and an orbicular phase. The composition of plagioclase, olivine and both pyroxenes are roughly the same in this phase as in the other differentiates.
Chapter 5

ORBICULAR GABBRO

GENERAL FIELD RELATIONS

Orbicular structures are found in the Lawson Peak gabbro in four small, irregular, elongate bodies (Plate I, back pocket). Three of these bodies are shown on Plate III (back pocket), a detailed geologic map of the main orbicular gabbro locality. Boundaries of the orbicular units are, like most of the other phases of the Lawson Peak gabbro, poorly exposed. Orbicules are generally densely packed into small lensoidal bodies (Figure 8); however, some free orbicules are found in hornblende gabbro within a few yards of the main outcrops of orbicular material (Plate III, back pocket) indicating that the main outcrops are surrounded by hornblende gabbro. Some plastic deformation occurs between orbs but usually this is not pervasive enough to produce interpenetration of one orb into another (Figure 9). A few orbicules appear broken but there does not appear to be any mixing of core material and matrix material in these cases (although the matrix comes into contact with the core.
Figure 8. Outcrop of Orbicular Gabbro. Scale is 50 cm.

Figure 9. Outcrop of Orbicular Gabbro. Note irregular shape and nature of contacts between the three orbs near the bottom of the outcrop.
of the orb).

Although orbs come very close together they do not actually touch; in all cases observed there is a thin (1 mm more or less) zone of matrix material which appears to have the same mineralogy as the rest of the matrix gabbro. The matrix material found filling all interstitial spaces around the individual orbicules appears to be constant in mineralogy and texture.

Individual orbicules range in size from less than 1 cm in diameter to over 30 cm in length. For the most part orbicules are not spheroidal, but rather are oblate spheroids with an average length:width ratio of 1.63:1 (based on 65 measured orbicules). A very minor percentage are extremely elongate with a length: width ratio of almost 10:1. In addition, some orbs have a very irregular outline. Both irregular orbs and elongate orbs appear to have a primary shape rather than having been produced by plastic deformation of an originally spheroidal orbicule.

Internally the majority of the orbicules consist of a core of medium-grained gabbroic material surrounded by a rim consisting of alternating layers of various mafic minerals (Figure 10). Some orbs, however, show only wide bands of radially oriented
Figure 10. Typical Orbicule (Groups 1 and 2) with Core of Medium-Grained Gabbronorite Surrounded by Rim Layers of Pyroxene, Plagioclase and Olivine (Olivine Not Found in Group 1 Orbicules)
pyroxenes with some plagioclase (Figure 11). Without exception this type of orbicule is much more spheroidal than the other types. Core types in the typical orbicule include what appears in hand specimen to be medium-grained amphibole gabbro or gabbronorite. Some have clot-like masses of mafic minerals at the center of the core surrounded by a plagioclase-rich zone. Others have a clot-like mass of plagioclase at the center of the core. A few orbicules contain previously-formed orbs as part of the core. This latter type is not abundant. It consists of a central core which appears to be a nearly complete orbicule. This is, in turn, surrounded by additional medium-grained gabbroic material which completes the core. One orbicule was observed with a core consisting of rhythmically-layered amphibole gabbro or gabbronorite (Figure 12). The most common rim type consists of alternating bands of mafic minerals averaging about 1 mm in thickness. The average thickness of this rim is fairly uniform, usually between 1 and 2 cm. Orbicules that consist of concentric bands of radial pyroxene crystals do not have this outer rim of alternating mafic layers.

PETROGRAPHY OF THE ORBICULAR PHASE

At the outset of this section it should be
Figure 11. Individual Orbicule (Group 3) Removed from Matrix Gabbronorite. Group 3 orbicules consist of bands of radially-oriented clinopyroxene crystals.
Figure 12. Orbicule with Core of Previously Formed Layering (Gabbronorite). Orbicule could be classed as either Group 1 or 2 (depending on whether or not olivine is present in the rim layers).
noted that due to the complexity and abundance of the orbicular structures, and the logistics of sampling and preparing thin-sections of these rocks, it was beyond the scope of this study to statistically analyze a large number of orbicular structures. More detailed work on these rocks may reveal variations and mineralogical/structural trends and affinities that are not shown by this study. A representative suite of orbicular rocks was collected and studied but it should be noted that this suite may not be statistically large enough to assure that all the variations and details were noted.

Determination of the modes of rim layers was accomplished using a modified version of an analytical technique developed for modal analysis of closed banded structures by Van Diver and Rabson (1970).

On the basis of petrography, three basic types of orbs can be distinguished.

Group 1: These consist of a core of medium-grained gabbroic material, surrounded by a rim of thin, alternating bands of various combinations of orthopyroxene, clinopyroxene, and plagioclase. No olivine is present in the rim layers.
Group 2: These consist of a core similar to that of Group 1 orbicules, surrounded by a rim of thin, alternating bands of various combinations of orthopyroxene, clinopyroxene, plagioclase, and olivine.

Group 3: These have no distinct core or rim layers, only concentrically arranged growth bands of radially oriented clinopyroxene. Plagioclase is present with the clinopyroxene along with minor amounts of orthopyroxene and olivine in narrow, granular layers separating radial clinopyroxene layers.

To better illustrate the mineralogy and structure of the various types of orbicules, the following are petrographic descriptions of a number of individual orbs. (Note: The "pigeonite" described below has the following optical properties: high relief, colorless with no pleochroism, inclined extinction, positive axial angle $2V = 5^\circ$ to $15^\circ$, second-order interference color, and simple twins with a single twin plane. Most of the pigeonitic clinopyroxene in these rocks has apparently inverted to orthopyroxene with concurrent exsolution of diopsidic (?) clinopyroxene as schiller lamellae and exsolution blebs.)

Group 1 (Sample ORB-7). The core of this
orbicule contains plagioclase, orthopyroxene, and minor amphibole. The orthopyroxene is interstitial to the other phases and has high relief, first-order yellow-red interference color, no distinct pleochroism, well-developed schiller lamellae, simple twins consisting of two individual twins with a single twin plane and a negative axial angle of 80°. Although many of these optical properties are characteristic of pigeonite, the axial angle indicates that this is an inverted pigeonite. Orthopyroxene poikilitically encloses plagioclase and is partially altered to amphibole. The amphibole has colorless to pale green pleochroism, first-order yellow interference color and a moderate (positive) axial angle, otherwise the optics are typical of amphibole. Based on optical data this is an edenitic amphibole. Plagioclase grains are equant, unzoned and unresorbed, and form a cumulus network with intergrain boundaries at 120° in all cases. Plagioclase composition in the core is between An75 and An80. Some altered cumulus olivine grains are found in the core. The rim layers of this orbicule consist of the following layers, proceeding from the core outward:

5.5 mm layer of large, slightly poikilitic, radially oriented pyroxene crystals, most of which have
a definite inward tapering shape. Most of these crystals have the optical properties of orthopyroxene but some have the optical properties of pigeonite. Thus, much of the orthopyroxene may be inverted pigeonite.

2.5 mm layer of large poikilitic, irregular, unoriented orthopyroxene.

6.5 mm layer of small, granular crystals of orthopyroxene.

1.0 mm layer of medium-grained, radially oriented orthopyroxene as in the layer adjacent to the core. As before, some of this pyroxene appears to be inverted or primary pigeonite.

A second orbicule rim is found adjacent to the first in this sample. The core material of this orb appears to be the same as the first in most respects and the rim consists of the following layers proceeding from the core outward:

7.5 mm layer of radially oriented, inward tapering poikilitic orthopyroxene most of which appears to be inverted pigeonite.

1.75 mm layer of granular, primary, unoriented orthopyroxene.

3.5 mm layer of radially oriented, inward tapering orthopyroxene. As in the layer adjacent to
the core, this orthopyroxene appears to be inverted pigeonite.

0.5 mm layer of granular, primary, unoriented orthopyroxene.

In the case of both of these orbicules, the rim layers are gradational into both the core and the matrix material surrounding the orbs. Plagioclase is present throughout the rim layers in varying proportions. Although the two orbs come very close to tangentially contacting each other in this sample, there does appear to be a thin band of matrix material between the two. The composition of the matrix in this case is approximately the same as in the core (i.e., gabbro-norite), however, texturally the pyroxene of the matrix is much more granular (cumulus) and is surrounded by an intercumulus amphibole showing colorless to pale green pleochroism.

Group 1 (Sample ORB-4). This sample contains two partial orbicules. The cores of both are incomplete, but all rim layers appear to be present. A zone of inter-orb matrix separates the two orbicules. The matrix in this case is composed of plagioclase, orthopyroxene, clinopyroxene with minor olivine and amphibole. Plagioclase forms a cumulus network of
interlocking grains with well-developed albite-carlsbad twinning and a composition of $\text{An}_{80}$ to $\text{An}_{84}$. Corroded, resorbed and altered olivine and rounded subhedral orthopyroxene (negative axial angle of $75^\circ$ to $80^\circ$ indicates a composition in the range of hyperssthene) are present as cumulus phases. Clinopyroxene (pigeonite, as previously described) is also present as a cumulus phase although it appears to have crystallized slightly later than olivine and orthopyroxene. Amphibole is present both as an alteration product formed at the expense of orthopyroxene and clinopyroxene and as the last intercumulus phase. This amphibole has colorless to pale green pleochroism, a positive axial angle and otherwise typical amphibole optics. Based on optical data the composition of this amphibole is edenite.

Rim layers of the first orbicule consist of (from the core margin outward):

- 7.2 mm zone of resorbed plagioclase and radially oriented pigeonite. The pigeonite poikilitically contains resorbed plagioclase and shows minor alteration to a pale green amphibole. The radial pigeonite crystals are terminated at the outer margin of this zone.
0.3 mm zone of poikilitic orthopyroxene and minor plagioclase. This zone has gradational boundaries with adjacent layers.

0.5 mm layer of granular orthopyroxene and plagioclase neither of which show resorption features.

0.4 mm layer of poikilitic orthopyroxene and minor plagioclase. Boundaries of this zone are gradational with adjacent layers.

5.0 mm layer of inverted pigeonite, orthopyroxene, and plagioclase with very irregular grain boundaries.

The second orbicule consists of the following layers (from the core margin outward):

6.2 mm layer of radially oriented pigeonite and plagioclase.

1.0 mm layer of poikilitic orthopyroxene and plagioclase.

1.4 mm layer of granular orthopyroxene and plagioclase.

1.0 mm layer of poikilitic orthopyroxene and plagioclase.

0.6 mm layer of granular orthopyroxene and plagioclase.
7.0 mm layer consisting of a mixture of anhedral pigeonite, orthopyroxene, and plagioclase.

In both cases the contact between the outer core and inner rim layers is represented by the large, radially oriented, terminated pigeonite crystals. The outer boundaries with the matrix are sharp and small grains from the outermost layers are found a short distance away in the matrix which has a distinctly larger grain size. It should be noted that pyroxenes in the matrix material are pervasively altered to amphibole, whereas pyroxenes in the core and rim of the orbicules show only minor alteration to amphibole.

Group 1 (Sample ORB-3). This sample consists of a single orbicule showing most of the core, a complete rim, matrix material surrounding the orb, and the partial rim of a nearby orb. The matrix material consists of cumulus plagioclase grains, cumulus orthopyroxene (optics: high relief, first-order interference colors, high negative 2V, schiller lamellae, parallel extinction, no twinning; composition in the enstatite-bronzite range), cumulus pigeonite, now mostly inverted to an orthohombic structure. Most of the pyroxene is altered to amphibole which also occurs as the solidus phase. This amphibole has
colorless to pale green pleochroism, first-order yellow interference color, positive axial angle and otherwise typical amphibole optics (composition based on optics is edenite). Plagioclase composition in the matrix averages around An$_{70}$.

The complete orbicule consists of a 5 to 6 mm zone in the outer core of radially oriented, inward tapering poikilitic pigeonite, minor orthopyroxene and plagioclase. This zone is not distinct on the inner (core) side but terminates abruptly at the outer margin of the core where some poikilitic orthopyroxene is found. The rim of this orbicule is 7 mm thick and consists of a combination of varying percentages of clinopyroxene, orthopyroxene, and plagioclase, none of which are poikilitic. No zones of distinctive mineralogy can be identified. The rim terminates abruptly at the outer margin where it contacts the matrix and only a few small grains of the outer rim are found in the matrix. The partial rim consists of an inner zone (maximum thickness of 1.5 mm) of poikilitic orthopyroxene and plagioclase which grades outward (toward the matrix) into an outer zone of poikilitic clinopyroxene, orthopyroxene (not poikilitic), and plagioclase and has a maximum thickness of 4 mm.
Group 2 (Sample ORB-6). The core of this orbicule consists of both ortho- and clinopyroxene, plagioclase, and minor amphibole. Plagioclase is generally large and equant with an average composition of $\text{An}_{80}$. No zoning is present but resorbed areas filled with pyroxene are common. Orthopyroxene is common in the inner core. It has first-order gray interference color, parallel extinction, high negative axial angle, schiller lamellae and pale pleochroism and is probably bronzite-hypersthene in composition. These crystals are granular, irregular and fill resorption patches in plagioclase. The outer core has large, radially oriented, inward tapering crystals of pigeonite that are poikilitic with respect to plagioclase. Optically this clinopyroxene is identical to pigeonite previously described.

The rim layers of this orbicule consist of (proceeding from the core outward):

2.5 mm layer of orthopyroxene with some pigeonite.

1.25 mm layer of granular olivine.

2.0 mm layer of granular olivine and orthopyroxene.

2.5 mm layer of olivine and plagioclase.
1.0 mm layer of orthopyroxene and plagioclase with orthopyroxene making up 70% of the layer.

0.7 mm layer of orthopyroxene and plagioclase with orthopyroxene making up 50% of the layer.

1.0 mm layer of orthopyroxene, clino- pyroxene, with minor plagioclase.

Amphibole (with the same optical properties as amphibole in other orbicules) occurs in minor amounts in the core and rim layers as an alteration product of both pyroxenes.

Group 2 (Sample ORB-2). The core of this orbicule consists of a central portion composed of a clot-like mass of cumulus orthopyroxene, clinopyroxene, with abundant intercumulus amphibole. On the basis of optical properties of these three minerals, the orthopyroxene has the composition of hypersthene, the clinopyroxene has the composition of pigeonite (some of which is now inverted to an orthohombic structure) and the amphibole with its pale greenish pleochroism appears to be edenitic. Plagioclase (An \textsubscript{78} to An \textsubscript{80}) is minor in this inner zone but becomes more abundant in the zone surrounding the inner core where it is found in abundance with radially oriented, inward tapering pigeonite crystals. This outer core extends for 4 mm
and gradually becomes finer-grained. The last 1.0 mm is a zone of medium-grained orthopyroxene, clinopyroxene, and plagioclase which terminates the radially oriented clinopyroxenes of the outer core.

The outer sequence of rim layers in this orbicule consists of:

1.2 mm layer of medium- to fine-grained orthopyroxene, olivine, and minor plagioclase.
1.0 mm layer of fine, granular olivine.
1.4 mm layer of fine granular orthopyroxene, olivine, and minor plagioclase.
0.6 mm layer of medium- to fine-grained, intimately intergrown orthopyroxene and clinopyroxene with some plagioclase.
1.0 mm layer of dominantly orthopyroxene and clinopyroxene and plagioclase in almost equal amounts.

Group 2 (Sample DRH 8-74-5C). The core of this orbicule has a central portion consisting of equant, unzoned cumulus plagioclase grains and rounded, poikilitic orthopyroxene grains (most of which have an enstatite-bronzite composition, but some appear to be inverted pigeonite). Progressing outward from this inner zone, plagioclase becomes increasingly more resorbed and filled with pyroxene with an increasing
abundance of radially oriented pigeonite. Plagioclase composition in the core ranges from An$_{75}$ to An$_{78}$. Orthopyroxene is found in increasing abundance in the outer portions of the core as small, irregular blebs in resorption patches. The rim of this orbicule is marked by a distinct and abrupt change from the radial pigeonite crystals of the core to the granular layers of the rim. The rim layers consist of (progressing outward):

3.0 mm layer of radial clinopyroxene (outer core).

1.5 mm layer of granular clinopyroxene, orthopyroxene and minor plagioclase.

0.6 mm layer of granular olivine, clinopyroxene, orthopyroxene, and minor plagioclase.

1.0 mm layer of granular clinopyroxene, orthopyroxene and minor plagioclase and olivine.

1.2 mm layer of granular olivine.

1.0 mm layer of coarse-grained orthopyroxene.

2.0 mm layer of fine-grained orthopyroxene, clinopyroxene and plagioclase.

Group 3 (Sample ORB-1). This orbicule has no discernable core or layered rim material, but consists
of radially oriented clinopyroxene (pigeonite) and plagioclase. There is no orthopyroxene visible in these radial layers but a granular, anhedral mixture of orthopyroxene (bronzite-hypersthene), plagioclase and minor olivine is found in fine-grained layers separating radial clinopyroxene zones. These layers average 0.5 mm in thickness and begin at the termination of the radial clinopyroxene crystals. The abundance of pigeonite in a particular zone increases steadily up to this zone, then ends abruptly. It is difficult to determine whether or not the pigeonite is poikilitic as it also contains abundant schiller structures and blebs of exolved diopsidic (?) material, produced upon inversion to the orthorhombic pyroxene structure.

Group 3 (Sample ORB-5). This orbicule has no distinct core or rim but instead has radially oriented materials in concentric layers. From core to rim it consists of the following layers:

17.5 mm of cumulus plagioclase (composition An$_{85}$ to An$_{88}$) with intercumulus orthopyroxene, surrounded in part by an amphibole with colorless to pale green pleochroism.

2.5 mm zone of first appearance of olivine.
Olivine crystals are subhedral to anhedral/irregular and fill resorption patches in plagioclase. There is no noticeable reaction between olivine and plagioclase as found in the main olivine gabbro phase. Orthopyroxene appears to have formed at the expense of olivine.

2.5 mm olivine zone, as above texturally, but olivine is much more abundant (90% to 100%).

2.5 mm zone of highly altered and serpentinitized olivine, but mostly orthopyroxene and plagioclase.

5.0 mm of plagioclase, orthopyroxene, and clinopyroxene (pigeonite, mostly inverted to orthohombic structure). Orthopyroxene and plagioclase are radially oriented and inward tapering.

1.0 mm zone of intercumulus, irregular, poikilitic orthopyroxene enclosing irregular resorbed plagioclase.

5.0 mm zone of orthopyroxene poikilitically enclosing irregular, resorbed plagioclase. There is some minor alteration of orthopyroxene to pale-green amphibole in this zone.
Several major faults or fault zones and many minor faults are found in the study area. The location of these fault zones is based on several lines of evidence including topographic expression, air photograph lineations, drainage patterns, truncated rock units, and shear zones in rock units. There are two systems into which faults in this area can be categorized. The more extensive of these contains all those faults with a general northwest-southeast trend. Faults having a general northeast-southwest trend form the second system and are much less extensive.

Northwest-Southeast Trending Fault System

Two major faults with this orientation are found in the study area. The first of these is located in the southern portion of the area and extends down a major ephemeral stream valley from near the junction of Deerhorn Valley Road and Lyons Valley-Japatul Road at the west margin of the map (Plate I, back pocket)
to Barrett Lake in the southeast corner of the map. The southwestern scarp (?) of this fault is a narrow, elongate ridge of tonalite and granodiorite which forms one of the boundaries of the triangular-shaped alluvial valley in the central portion of the area. Other geologic maps (of a more regional nature) show this to be an extension of the Hauser Canyon fault which has a known vertical component of recent movement (upthrown block to the south) (R. L. Threet, oral communication, 1975). Thus, motion of a vertical nature on this fault could have produced the steep ridge in the southern part of the study area.

The second major fault of this system crosses the area with a more northerly trend. It extends from Lawson Valley in the northwest corner of the map to Barrett Lake in the southeastern corner of the map, where it appears to join with the Hauser Canyon fault. This fault crosses the main mass of the Lawson Peak gabbro. It appears to offset the contact between the gabbro pluton and the granodiorite with a left-lateral sense of displacement, truncates a major pegmatite dike and appears to offset another pegmatite dike with a right-lateral sense of relative motion. This seemingly contradictory type of displacement could be produced by dip-slip movement along the fault (upthrown
block to the northeast) if the granodiorite-gabbro contact dips steeply to the northwest (which it appears to do) and the pegmatite dike dips steeply to the southeast. Evidence for the absolute sense of movement along either of these two northwest-southeast trending faults is not present. If the presumed sense of motion along these two faults is correct, then the valley in the central part of the map is a triangular-shaped, graben-like structure.

**Northeast-Southwest Trending Fault System**

Several small linear features with this orientation can be located in the area by means of air photograph interpretation. These are concentrated around the more northerly of the two northwest-south-east trending faults and may in some way be related to stresses which produced the more extensive shear zone. As before, positive evidence for the existence of this second group of faults is also lacking.

**FOLIATION IN GRANODIORITE**

Lineations in granodiorite outcrops can be easily seen on air photographs of the area, but only those orientations which were actually measured in the field are plotted on the geologic map (Plate I, back
pocket). Orientations measured in the field and determined from air photographs are concordant and show the same general trend of lineation in the granodiorite. Lineations are most prominent near the contact with the gabbro pluton and, in all observed cases, lineations are parallel or subparallel to the contact. It is possible that this lineation is a manifestation of cryptic (not particularly well-developed in outcrop) flow-lineation or foliation of the platy minerals in the granodiorite. If this is the case, then the lineation formed as the granodiorite intruded the area and flowed around the already solidified gabbroic pluton. Lineations seen on air photo mosaics of the granodiorite of the Peninsular Ranges batholith of Southern California seem to support this hypothesis.

ORIENTATION OF INCLUSIONS AND SCHLIEREN IN TONALITE

Schlieren sections in the tonalite are found bordering the gabbro pluton in several places. Schlieren zones are gradational into zones rich in lensoidal, elongate, diorite-like inclusions. These zones are not as rich in inclusions as the schlieren zones, have much more tonalite between inclusions, and are gradational into relatively inclusion-free tonalite.
In all instances schlieren units and nearby inclusions are aligned parallel or subparallel to the gabbro-tonalite contact. Further from the contact inclusions show no preferred orientation, as in the southern portion of the study area.

To summarize, lineations in the granodiorite and tonalite indicate formation by flow around the pre-existing gabbroic pluton. The shear zones do not appear to be related to either of the rock types. These shear structures are probably related to other major northwest-southeast trending structural features of Southern California, for example, the San Andreas and Elsinore fault zones.
Chapter 7

DISCUSSION

PETROGENETIC MODEL

The parental magma from which the various rock types of the Lawson Peak gabbro were derived was probably produced by partial melting of the upper mantle. The exact composition of this magma is unknown as there is no chemical data available for this pluton. The various rock types could be formed by crystallization from a variety of parent melts including those of tholeiite, alkali-olivine, and high-alumina basalt composition. Chemical studies of similar plutons in the Southern California Peninsular Ranges batholith by Larsen (1948) and Nishimori (1974) suggest that the parent melt had high-alumina basalt affinities. Experimental work by Kushiro and Thompson (1972) shows that the mineralogy and sequence of crystallization observed in this pluton can be produced by crystallization of a parent melt with a high-alumina plagioclase tholeiite composition. For the purposes of this discussion the composition of the parent magma for the Lawson Peak pluton is therefore assumed to be high-alumina plagioclase
tholeiite.

Once formed, the parent magma intruded the crust with a diapiric style of intrusion. The exact composition and physical properties of the material intruded are unknown as the gabbro is the oldest exposed unit in the area studied. Studies of similar plutons in the area show that the gabbro probably intruded prebatholithic metasediments, locally termed the Julian schist (Larsen, 1948), as in the Los Pinos pluton to the east of Lawson Peak (M. J. Walawender, oral communication, 1975).

The observed distribution and mineralogy of the various rock types in the Lawson Peak pluton suggests that these rocks were produced by differentiation and crystal settling. Primary evidence for differentiation processes comes mainly from mineralogy and cumulate textures of the mafic-rich phases of the pluton. In all cases calcic plagioclase and olvine are the liquidus phases and invariably exhibit cumulate textures with orthopyroxene and amphibole (solidus phases).

The conditions of formation and, in particular, the depth at which crystallization of the various phases of the pluton took place can be inferred from several lines of evidence. One line of evidence is the
anorthite-olivine reaction corona developed around some olivine grains. It is very difficult to determine the actual composition of the orthopyroxene-like material on the olivine (inner) side of the corona due to its small size. If it is orthopyroxene, then this corona is quite similar to those described by Gardner and Robins (1974), Hatch and others (1973), and other writers. According to experimental work by Green and Ringwood (1967, 1972) and Kushiro and Yoder (1966) this subsolidus reaction between plagioclase and olivine to form spinel and orthopyroxene forms at a minimum pressure of about 8 kilobars at magmatic temperature and under anhydrous conditions. Because of difficulty in obtaining exact (petrographic) compositional data on the mineralogy of the coronas and considering that this reaction is not taking place under controlled laboratory conditions, it is not possible to bracket the formation of these coronas into a particular pressure-temperature environment. If the orthopyroxene-like material in these coronas is actually a hydrous phase, then it is possible that this reaction would take place at lower pressures. Other lines of evidence suggest much lower pressure (i.e., shallower depth) of crystallization of magma. Field evidence for shallow emplacement of the gabbro is seen in other nearby
plutons. The Los Pinos pluton has a chilled marginal phase in contact with the prebatholithic Julian schist, which indicates a fairly shallow level of emplacement (M. J. Walawender, oral communication, 1975). Assuming that the gabbro plutons of this area are essentially in place, other evidence for shallow emplacement is found in the felsic rock units. Duffield and Jahns (1975) have demonstrated that rocks of the Peninsular Ranges batholith were emplaced at shallow crustal levels (at depths less than 5 kilometers). The most convincing line of evidence comes from experimental work by Kushiro and Thompson (1972). They showed that the observed mineralogy and sequence of crystallization (plagioclase followed by olivine and later by pyroxene) in the Lawson Peak pluton can be produced by crystallization of high-alumina plagioclase tholeiite (hydrous) at pressures not exceeding 5 kilobars. However, the occurrence of clinopyroxene (pigeonite) in some phases of the pluton as a liquidus phase indicates a pressure of crystallization greater than 5 kilobars (Kushiro and Thompson, 1972). Therefore, although portions of the magma may have begun crystallization at pressures in excess of 5 kilobars, the majority of crystallization took place at a maximum pressure of 5 kilobars.
After generation of the parent melt, the magma intruded the crust diapirically. This intrusion produced a narrow, elongate conduit zone extending from the point of generation to a magma reservoir at depth, which will be referred to as level 1. Crystallization began in this reservoir with clinopyroxene on the liquidus. As shown by Kushiro and Thompson (1972) clinopyroxene on the liquidus in a magma of this composition indicates a depth of formation greater than about 18 kilometers (pressure greater than 5 kilobars). Early formed clinopyroxene (~calcic plagioclase) settled to the lower portions of the reservoir, thus depleting the upper portions in the components necessary to form clinopyroxene.

When a certain amount of clinopyroxene (~plagioclase) had crystallized and settled, the upper portion of the reservoir separated from the parent melt at level 1 and moved diapirically upward. The composition of this daughter melt was that of the hornblende gabbro phase of the Lawson Peak gabbro. At shallower levels in the crust this daughter melt came to rest in a second magma reservoir, possibly a subvolcanic reservoir. This second magma reservoir will be referred to as level 2. Crystallization began at
level 2 with plagioclase on the liquidus. As crystallization proceeded the volatile content of the melt increased (due to crystallization of anhydrous plagioclase) producing amphibole at the expense of pyroxene as the solidus phase.

In all rocks of the main hornblende gabbro phase the plagioclase shows a major period of resorption and subsequent crystallization of rim material with a lower anorthite content. This resorption could be explained by the release of total pressure on the system through movement of the magma from level 1 and emplacement at level 2 (Vance, 1965). A second possible explanation for this feature was proposed by Jorgenson (1971). This process, explained using the phase relations in the system diopside-albite-anorthite (Lindsley and Emslie, 1968), involves the increase of water pressure on the system which shifts the ternary cotectic between plagioclase (solid-solution) and pyroxene into the field of plagioclase (i.e., reduces the field of plagioclase). This results in the resorption of plagioclase with subsequent crystallization of a rim of lower anorthite content. This increase of water pressure on the system could be related to movement of the magma from level 1 to level 2. Emplacement at shallower levels will result in decreased solubility
of water in the melt. The closer approximation to water saturation may yield higher water pressure than at depth where the melt was strongly undersaturated in water. Thus, even though the system is at lower total pressure, water pressure may be increased.

At this point, with the main hornblende gabbro phase crystalline, the clinopyroxene-enriched material left at level 1 was remobilized and migrated upward along the same conduit zone. The composition of this second intrusion from lower levels is equivalent to that of the gabbronorite phases of the pluton. That is, the composition of the gabbronorite magma is equivalent to that of the parental melt plus the clinopyroxene separated in level 1. As the gabbronorite intruded to shallower levels, the clinopyroxenes formed at level 1 were resorbed. It should be noted that the only 2-pyroxene (ortho- and clinopyroxene) rocks of this pluton are those related to the gabbronorite. In all cases the clinopyroxene (pigeonite) is resorbed and in some cases is inverted to orthopyroxene. The hornblende gabbro contains only augitic clinopyroxene but as cores to the hornblende. In restricted areas of the pluton, crystallization began with plagioclase and olivine on the liquidus, followed by
pyroxene. Gravity differentiation of these crystals in restricted chambers produced the differentiated phases (peridotite, olivine gabbro and anorthosite). The hornblende gabbro was the host rock for these restricted differentiation chambers. Further crystallization increased the volatile concentration in the melt resulting in the formation of the "spotted" (poikilitic) and pegmatitic phases in the gabbronorite. Both these phases indicate crystallization under water-excess conditions. The orbicular phase is also related to the increase of volatiles in the system but its origin will be considered later in this chapter. The occurrence of pigeonite in the poikilitic, pegmatitic, and orbicular phases suggests that the formation of this mineral is favored over others by an increased volatile content (water-excess conditions) in the melt at pressures < 5 kilobars.

The fine- and medium-grained phases of the gabbronorite were also produced by the movement of material from level 1 into the hornblende gabbro at level 2. In the field, both units are intrusive into the hornblende gabbro. The texture of the fine-grained phase could either be the result of chilling against the cooler hornblende gabbro or caused by a pressure
release, possibly through venting to the surface (i.e., a quench texture). The medium-grained phase followed and is clearly intrusive into the fine-grained gabbronorite. The texture of this phase could be produced simply by slower cooling as a result of higher temperatures in the surrounding rock. If there was a substantial increase of heat in the host rock (essentially a closed system) by intrusion of the fine-grained phase, then the temperature may have been increased enough to allow slower cooling of the medium-grained phase. On the other hand, if there was no release of confining pressure, the coarser grain size could have been produced by an increase of volatile components.

The solidus phase in the differentiates and other phases of the gabbronorite is an edenitic amphibole. Early removal of clinopyroxene at level 1 and removal of the hornblende gabbro magma may have increased the activity of sodium and possibly aluminum so that an edenitic amphibole instead of common hornblende would be favored as the final solidus phase.

Verification of this model will require bulk chemical analyses of the various phases of the pluton and mineral chemistry of clinopyroxene in the gabbronorite. These analyses will show whether it is possible
to produce the hornblende gabbro by early separation of clinopyroxene from a high-alumina basaltic melt.

Several features of the Lawson Peak gabbro suggest that the magma chamber at level 2 was a subvolcanic reservoir. The multiple intrusive character of the pluton suggests that there were periodic releases of material to the surface (via venting). That is, as material is released to the surface, fresh magma from deeper levels would rise into the subvolcanic reservoir to take its place. Considering the shallow depths at which the pluton was emplaced, it seems reasonable to assume that some magma would migrate to the surface at periodic intervals. Other gabbroic bodies in the area, such as the Los Pinos pluton, have features similar to this pluton that are attributed to processes in a subvolcanic reservoir (Walawender and Walawender, 1974). It is possible that the pressure fluctuations in the volatile-rich channels that produced the orbicular phases are related to venting to the surface. However, these fluctuations can be explained in other ways and are not conclusive evidence of subvolcanic processes.

ORIGIN OF THE ORBICULAR PHASE

There are a number of theories of orbicule
formation, most of which can be found in the literature referred to in the introduction. On the basis of this previous work and the present study, three basic modes of formation can be suggested for these orbicular rocks.

1. Outward crystallization of minerals in a medium of relatively low viscosity. This is similar to orbicule formation in hydrous-rich channels as proposed by Moore and Lockwood (1973).

2. Inward crystallization of minerals in a restricted, closed system (i.e., crystallization of pockets of "trapped" liquid).

3. Metamorphic or metasomatic processes.

The last of these modes (3) will not be considered in this discussion, as orbicules in this pluton are clearly the result of magmatic processes. Evidence from the present study is not conclusive as to which of the other two processes best explains the origin of the orbicules in this pluton. As an example, both inward and outward growth of minerals could produce the radially oriented, inward tapering crystals seen in these orbicules.

Assuming for the moment that these orbs form by mineral growth from the rim inward towards the center, several problems arise. If the orb is initially
sealed to trap the interior liquid then there should be a progressive increase in volatiles towards the center as crystallization of anhydrous phases proceeds. This should produce features in orbicule cores similar to those in pegmatite bodies. No such features are observed in these rocks. If the growth is from the rim inward, how is it possible to produce orbicules with xenolith cores (Figure 12, page 48) or previously formed orbs at the center? If rim layers represent material that enclosed the liquid which then crystallized, how do the rims form in the first place? Is it possible that rim layers formed as flat, layered units on walls of the conduit zone, fragments of which periodically are detached from the wall and "wrap up" liquid? The actual mechanics of such a process are complicated, improbable, and still leave questions such as why there are no incompletely formed orbs and how it is possible to wrap up irregular or elongate cores.

In an attempt to simplify the origin of these rocks it is proposed that these orbicules form by radial growth of minerals from the center outward. Some of the features that suggest this origin are the variety of core types (including xenoliths and other
orbicules), the mineralogy and texture of the cores, abrupt changes in crystallization (i.e., terminated pigeonite crystals) and the presence of poikilitic pyroxene and resorbed plagioclase internally and in rim layers. On the basis of field distribution and the mineralogical-textural features already noted, the following theory is proposed for the origin of the orbicular rocks of this pluton.

Various features of the orbicular rocks of this pluton suggest a mode of formation similar to that proposed by Moore and Lockwood (1973) for orbicular rocks of the southern Sierra Nevada. As the volatile content of the gabbro-norite magma increased (by crystallization of anhydrous phases) it is reasonable to assume that volatile-rich channels or pipes could form in restricted portions of the magma chamber. Volatile streaming in these channels would disrupt fragments of wall rock and include them in the channel where they would become sites of nucleation for crystallization. This would account for the variety of core types found in these orbicules. Crystallization around these fragments suspended in the melt produced the long, inward tapering, radial clino-pyroxene (pigeonite) crystals found in all orbicules.
At a particular stage of orbicule growth there is a substantial reduction of volatile content in the melt as a result of a pressure drop (via venting to the surface). This reduction of volatile content produces two features. The first and most obvious feature is the termination of growth and resorption of radial clinopyroxene. The second feature is the granular rim layers on types 1 and 2 orbicules. The mineral assemblages in these rims (plagioclase, orthopyroxene, and olivine) indicates formation under pressure conditions less than 5 kilobars (Kushiro and Thompson, 1972) and reduced volatile content as in the pigeonite-free phases of the gabbronorite. Also, the granular, fine-grained nature of the rims may indicate more rapid crystallization due to a pressure drop in the system.

During the final crystallization of rim layers fluctuations in water pressure would have considerable effect on determining the phases that would precipitate. Assuming for the moment that the composition of this magma would fall near the ternary eutectic in the forsterite-diopside-silica system (Coombs, 1963), then an increase of pressure under hydrous conditions causes an expansion of the forsterite field (Kushiro, 1969). Under anhydrous pressures, however, the field of
forsterite is reduced. So, for a given composition near the ternary eutectic in this system, fluctuating water pressure could shift the olivine-pyroxene cotectic to produce alternating layers of orthopyroxene, clinopyroxene, and olivine. These fluctuations of water pressure, seen also in the hornblende gabbro, could possibly be related to periodic venting to the surface. Once the rim layers had become a few mm thick, the core of the orbicule became essentially solid and closed to any vapor phase migration. This accounts for the lack of extensive alteration to amphibole in the orbicule cores.

After most of the rim layers had formed by rhythmic crystallization, many of the orbicules collected and were concentrated into certain portions of the volatile-rich channel. It is possible that they settled into flattened areas of the channel, accumulated beneath a roof, or were driven into lateral re-entrants as suggested by Moore and Lockwood (1973). This produced the densely-packed orbicular bodies which show slight plastic deformation between adjacent orbs. Following this accumulation of orbicules the gabbronorite liquid crystallized around the orbicules. The typical medium-grained texture of this matrix
material indicates that at this later stage the volatile enrichment in the channel had been reduced substantially (possibly by continued pressure release via venting to the surface and influx of new, water-unSATURATED MELT) so that the matrix crystallized under the same conditions of pressure and volatile content as the rest of the gabbronorite magma (with the exception of the poikilitic and pegmatitic phases).

A complete lack of rim layers in type 3 orbicules indicates that these represent an arrested stage of growth of radial clinopyroxenes. It is possible that these orbicules were surrounded by more viscose magma along the walls of the channel. As this material crystallized, the orbicules were insulated from further growth.

SUMMARY OF PETROGENESIS

The basic steps of magmatic evolution to produce the observed distribution of rock types in the Lawson Peak pluton can be summarized as follows:

1. Generation of a high-alumina plagioclase tholeiite parent magma by partial melting of the upper mantle. Experimental work suggests a depth of magma generation of at least 25 kilometers. This depth may imply oceanic crust overlying the area of magma
generation.

2. Diapiric-style intrusion of the parent magma to produce a narrow, elongate conduit zone extending from the zone of magma production to a magma reservoir at a depth greater than about 18 kilometers (level 1).

3. Initial crystallization of clinopyroxene (+ plagioclase) and removal of these early phases to the lower portions of the magma reservoir (level 1).

4. Remobilization of the clinopyroxene-depleted upper portions of the magma reservoir to a shallower level in the crust (level 2). The material intruded at this stage was probably preexisting pelitic (marine) sediments, again suggesting oceanic crust overlying the area of magma generation and intrusion. Crystallization at this level with plagioclase on the liquidus would begin at pressures less than 5 kilobars to form the main hornblende gabbro phase.

5. Remobilization of the clinopyroxene-enriched (gabbronorite) lower portions of the reservoir at level 1. The gabbronorite magma intruded the partially crystalline hornblende gabbro phase at level 2. In restricted portions of the magma chamber differentiation of the gabbronorite produced the
olivine gabbro, peridotite and anorthosite phases of the pluton. Crystallization of anhydrous phases increased the volatile content of portions of the magma resulting in the "spotted" (poikilitic), pegmatitic, and orbicular phases of the gabbronorite. The orbicules formed in volatile-rich channels or pipes similar to those described by Moore and Lockwood (1973).

6. Periodic venting to the surface is suggested by the multiple intrusive character of the pluton, the shallow crustal level at which it was emplaced, and comparison to similar plutons in the area which show evidence of formation in a subvolcanic reservoir.
Chapter 8

RECOMMENDATIONS FOR FURTHER STUDY

The limited area studied precludes making any broad conclusions as to the relation of this pluton to the formation of the Peninsular Ranges batholith. However, further study of gabbroic plutons in the batholith are necessary to make these conclusions. The following recommendations can be made as to the direction of these studies.

1. The lithology, structure, and distribution of rocks older than the gabbro and into which the gabbro is intrusive should be studied in detail, in the field as well as petrographically and chemically. This would allow more definite conclusions as to the pressure-temperature conditions of intrusion of the gabbro.

2. Detailed mapping and sampling of these plutons at a scale smaller than 1:24,000. Due to the complex variations internally, much detail regarding gradational contacts and distribution of rock types is lost when mapping at a scale of 1:24,000 (as shown by comparing Plates I and III, see back pocket).

3. Complete chemical analyses of the various
rock types, both bulk chemistry and mineral chemistry, are necessary to make any conclusive statements about the origin and composition of the parent magmas for these plutons.

4. An attempt should be made to correlate the gabbroic rocks of the Peninsular Ranges batholith with volcanic rocks of similar age. Ideally, this would necessitate finding a complete sequence of plutonic, hypabyssal, and volcanic rocks all temporally and spatially related.

A number of authors have made the statement that the gabbroic rocks of this area cannot be mapped at a scale of 1:24,000 due to the complex internal variations. If nothing else, this study should show that not only can the complex internal variations of these plutons be represented at this scale, but that it is essential that all the plutons in the area be mapped accordingly so that more detailed studies have a firm foundation on which to begin.
REFERENCES CITED
REFERENCES CITED


APPENDIX A

AVERAGE MINERALOGIC MODES FOR ROCKS OF THE LAWSON PEAK GABBRO
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APPENDIX B

CLASSIFICATION OF ROCKS OF THE LAWSON PEAK GABBRO, BASED ON MINERALOGIC MODES AND I.U.G.S. SYSTEM OF ROCK CLASSIFICATION
## CLASSIFICATION OF ROCKS OF THE LAWSON PEAK GABBRO,
BASED ON MINERALOGIC MODES AND I.U.G.S. SYSTEM
OF ROCK CLASSIFICATION

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APPENDIX C

AVERAGE MINERALOGIC MODES OF THE FELSIC ROCK UNITS
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*Inclusions in tonalite of the Bonsall type.
APPENDIX D

CLASSIFICATION OF THE FELSIC ROCK UNITS
BASED ON THE I.U.G.S. CLASSIFICATION SYSTEM
### Classification of the Felsic Rock Units Based on the I.U.G.S. Classification System

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*Inclusions in tonalite of the Bonsall type.*
ABSTRACT
ABSTRACT

The Lawson Peak gabbro body, a unit of the Peninsular Ranges batholith of Southern California, is located twenty-five miles east of San Diego, California. Field relations indicate that the gabbro is older than the surrounding granodiorite of the Woodson Mountain type and tonalite of the Bonsall type. Potassium-argon ages on the gabbro are $129.1 \pm 18.6$ MYBP on hornblende and $99.6 \pm 3.1$ MYBP on plagioclase.

The gabbro consists dominantly of hornblende gabbro, with smaller amounts of olivine gabbro, pyroxene-hornblende gabbronorite, and lensoidal peridotite and anorthosite. The gabbronorite shows a wide variation in mineral proportions as well as scattered, discontinuous units of alternating plagioclase- and mafic-rich layers. Textural variations range from fine-grained phases to pegmatitic segregations. Locally the gabbronorite has abundant orbicular structures. These are roughly spheroidal, range in size from 1 cm to 30 cm, have an average length:width ratio of 1.65:1, and are slightly deformed and concentrated into narrow, lensoidal bodies. They consist of a core of medium-grained gabbronorite surrounded by a rim of
rim of 1 to 2 mm alternating layers of granular pyroxene and olivine.

The various rock types in this pluton were produced from a parent magma with high-alumina plagioclase tholeiite affinities. Removal of early-formed clinopyroxene in a magma reservoir at depth ($P > 5$ kb) produced a Cpx-depleted upper portion which separated from the parent melt and intruded to shallow crustal levels. This daughter melt crystallized to form the hornblende gabbro phase in a shallow magma reservoir ($P < 5$ kb). Later the Cpx-enriched lower portion of the parent magma at depth was remobilized and intruded the partially crystalline hornblende gabbro. This second pulse of gabbronorite magma differentiated to produce the various mafic-rich phases of the pluton. Volatile enrichment in portions of the gabbronorite magma produced the "spotted" and pegmatitic phases. The orbicular structures appear to have formed in volatile-rich channels in the gabbronorite (Moore and Lockwood, 1973).
PLATE I. GEOLOGIC MAP OF THE LAWSON PEAK ORBICULAR GABBRO

EXPLANATION

- Quaternary alluvium
- Granodiorite (Ponson Mountain type)
- Tonalite (Bonsall type)
- Lawson Peak gabbro
  - Olivine gabbro
  - Anorthosite & anorthositic gabbro
  - Peridotite
  - Orbicular hornblende gabbro

- Major drainage
- Major roads
- Faults (dashed where approximate or inferred)
- Contacts (dashed where approximate)
- Pegmatite & felsic veins & dikes
- Strike and dip of lineations

BASE MAP DATA TAKEN FROM BARRETT LAKE 7.5' QUADRANGLE, UNITED STATES GEOLOGICAL SURVEY

INDEX MAP

DAVID RUSSELL HOFFMAN
PETROGENESIS OF THE LAWSON PEAK ORBICULAR GABBRO
MAY 1975
PLATE II. GENERALIZED GEOLOGIC MAP SHOWING LOCATIONS OF SAMPLES DESCRIBED IN TEXT

EXPLANATION

CENOZOIC

QUATERNARY ALLUVIUM

WOODSON MOUNTAIN GRANODIORITE

BONSTELL TONALITE

LAWSON PEAK GABBRO (undivided)

SAMPLE LOCALITY, PETROGRAPHY DESCRIBED IN TEXT.

BASE MAP DATA TAKEN FROM BARRETT LAKE 7.5' QUADRANGLE, UNITED STATES GEOLOGICAL SURVEY

MAJOR DRAINAGE
MAJOR ROADS
CONTACTS (dashed where approximate or inferred)

SCALE = 1:24,000

INDEX MAP

DAVID RUSSELL HOFFMAN
PETROGENESIS OF THE LAWSON PEAK ORBICULAR GABBRO
MAY 1975
PLATE III. GEOLOGIC MAP OF ORBICULAR GABBRO LOCALITY

EXPLANATION

HORNBLende GABBRO / "SPOTTED" GABBRO

ORBICULAR HORNBLende GABBRO

OLIVINE GABBRO

PERIDOTITE

ANORTHOSITIC GABBRO

SAMPLE LOCALITIES

INDIVIDUAL ORBICULES

INDEX MAP

SCALE = 1:24,000

DAVID RUSSELL HOFFMAN
PETROGENESIS OF THE LAWSON PEAK ORBICULAR GABBRO
MAY, 1975

TOPOGRAPHIC DATA AND INDEX MAP TAKEN FROM GARRETT LAKE 7.5' QUADRANGLE, UNITED STATES GEOLOGICAL SURVEY, 1965

SCALE = 1:1225

(ApPROXIMATE)