GEOLOGY, PETROLOGY, AND GEOCHEMISTRY OF THE
VIEJAS MOUNTAIN GABBRO PLUTON
SAN DIEGO COUNTY, CALIFORNIA

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
Richard Jack Allinger
Spring 1979
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Approved by:

Michael Walawender
Thesis Chair

Date

Brad Bartel
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Chapter 1

INTRODUCTION

The Peninsular Ranges batholith extends southward from the Transverse Ranges on the north through the state of Baja California and averages about 100 km in width. The western margin of the batholith intrudes Upper Jurassic and Middle Cretaceous volcanic and volcaniclastic rocks of andesitic composition. The volcanic rocks rest on Late Triassic to Late Jurassic marine strata and are largely buried by postbatholithic sedimentary rocks. Prebatholithic nonvolcanic sedimentary rocks of Mesozoic to Late Paleozoic age are found in the medial portion of the batholith.

The batholith was divided into three subbelts by Gastil, Krummenacher, Doupont, and Bushee (1974). The gabbro subbelt lies on the Pacific side of the batholith, whereas the medial tonalite and interior adamellite subbelts lie respectively farther east. The gabbro subbelt consists of up to 20% gabbro. Gabbro plutons are not found in the two interior subbelts.

Other workers have discussed the general geology of the batholith noting that the bulk of the rocks are granodiorite and range from peridotite to granite
(Miller, 1937; Larsen, 1948; Everhart, 1951). Their general sequence of emplacement in the batholith is: Gabbro—>Tonalite—>Granodiorite—>Granite.

The Viejas Mountain gabbroic pluton lies within the Peninsular Ranges batholith about 2 km northeast of Alpine, California (Figure 1). The pluton is sub-elliptical in shape with steep slopes that give rise to radial drainage. The pluton underlies about 8-10 square km. The contact between gabbro and younger granitic rocks is at about 3,200 feet elevation on the north slope and 2,200 feet elevation on the south slope of the mountain. The pluton is characterized by a thick brush cover, ubiquitous screen, and a thick soil horizon. Rock exposures are isolated and usually consist of large fractured boulders, many of which have moved downslope.

No detailed study of the Viejas Mountain pluton has been completed prior to this work. Even (1975) discussed the general geology and petrography of selected gabbroic rocks, and his work is reinterpreted in this report. Viejas Mountain has been discussed briefly or mentioned by several authors, but usually in regional reports (Miller, 1937, 1938; Merriam, 1946; Everhart, 1951). Other gabbroic plutons in the Peninsular Ranges have recently been studied (Hoffman, 1976;
Figure 1. Location Map for the Viejas Mountain Gabbroic Pluton
Nishimori, 1976; Walawender, 1976; Lillis, 1978). Each of the above studies presents detailed geochemical and/or petrographic analyses of the gabbroic rocks and discussions on the origin and emplacement histories of the plutons.

The purpose of this study was to determine the origin and emplacement history of the Viejas Mountain gabbro pluton through detailed geologic mapping, petrography and geochemistry. Field mapping was completed during Fall 1977 and Spring 1978 using the U.S.G.S. 7-1/2 minute Viejas Mountain quadrangle. Thirty-eight thin sections were studied using standard flat-stage petrographic techniques. Plagioclase compositions were determined by combining spindle stage techniques (Wilcox, 1959) with index oil immersion techniques. Thirteen whole rock samples were analyzed for major and trace element abundances.
Chapter 2

PETROGRAPHY

Prebatholithic Rocks

Undivided prebatholithic metamorphic rocks are exposed on the margins of Viejas Mountain as several isolated roof pendants and inclusions. A small (about 500 square m) roof pendant of metamorphic rocks is exposed in the northeast corner of the map area sandwiched between exposures of gabbroic rocks and granitic rocks. The rocks are highly weathered and form a surface of low relief between the prominent hills of granitic rock and gabbro. A traverse from the roof pendant eastward toward Poser Mountain shows a mixed zone of schist and tonalite. The main lithology is quartz-mica-feldspar schist but within the mixed zone there are small inclusions of diopside skarn. A smaller roof pendant of highly weathered schist was found on the west flank of the pluton at boundary road (Plate I, back pocket). Berggreen and Walawender (1977) studied a nearby roof pendant and reported the lithologies ranging from quartz-biotite-feldspar schist, quartzite, and metaconglomerate to diopside skarn.
Tonalite-Diorite

The Viejas Mountain gabbro is surrounded by tonalites that have previously been mapped as Bonsall Tonalite and Green Valley Tonalite (Everhart, 1951; Even, 1975). These rocks, which are not divided in this report, consist of hornblende-biotite tonalite and pyroxene-biotite diorite to quartz diorite. Rock nomenclature follows Streckeisen (1973). Locally they contain up to 15% potassium feldspar and poikilitic biotite. Inclusions in the tonalite are abundant and consist of rounded and/or elongate fragments of mafic rock. Foliation in the tonalite is defined by a parallel alignment of mafic minerals and by the elongate mafic inclusions. The foliation is always steeply dipping to vertical and subparallel to the contact with gabbro. The attitude of the foliation suggests that the tonalite intruded gabbro at steep angles.

Surficial Deposits

The most conspicuous aspect of the surface deposits is the abundance of colluvium (QC) and landslides that nearly surround the mountain. Even (1975) placed the gabbro-tonalite contact at the base of Viejas Mountain but the contact is well up the sides of the
mountain (Plate I, back pocket). Alluvium (Qa) consists of sand, gravel, and mud deposited in the large valley east of Viejas Mountain. Colluvium consists of poorly-sorted gravels, boulders, sand, and mud deposited on the flanks of Viejas Mountain.

**Gabbroic Rocks**

**Introduction**

The gabbroic rocks of Viejas Mountain are divided into five mappable units (Plate I, back pocket) and include troctolite, plagioclase porphyry, two-pyroxene olivine gabbronorite, leuconorite and hornblende gabbro (Table 1). Rock nomenclature follows (Streckeisen, 1963). Troctolite and plagioclase porphyry are exposed in a subelliptical zone at the southern end of Viejas Mountain. Two-pyroxene olivine gabbronorite is exposed in two isolated "pods" at the summit of the mountain and on the west flank. The remainder of the pluton is composed of leuconorite, with the exception of one isolated exposure of hornblende gabbro (Plate I, back pocket). Contact relationships between the rock types are generally obscured. Troctolite is considered the oldest gabbroic unit followed by plagioclase porphyry, two-pyroxene olivine
Table 1
Modal Analyses of Group 1 and Group 2 Rocks

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<td>82/86</td>
<td>82/86</td>
<td>86/89</td>
<td>71/74</td>
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<sup>a</sup>Mafic Dike.  
<sup>b</sup>Minimum/Maximum.
gabbronorite and leuconorite. Inclusions of trocto-lite are found in the plagioclase porphyry, and the other rock types, including plagioclase porphyry, are seen as inclusions in the leuconorite.

For ease in interpretation in the following sections, the rocks are divided into two groups based on petrographic and geochemical parameters (Table 1, page 8). Group 1 includes troctolite plagioclase porphyry and two-pyroxene olivine gabbronorite, whereas Group 2 consists of leuconorite which is subdivided into two units. Group 1 rocks are characterized by the presence of olivine as a cumulate phase and interstitial orthopyroxene. Group 2 is characterized by lack of olivine, prismatic orthopyroxene, and resorbed clinopyroxene.

Group 1

Troctolite. The contact between troctolite and porphyry is not exposed, but appears to be sharp. Troctolite typically contains plagioclase, olivine, and variable amounts of orthopyroxene (Table 1, page 8). Plagioclase is the most abundant phase and occurs as unzoned euhedral to subhedral laths with complex carlsbad, albite and pericline twinning. The plagioclase often displays deformation twin lamellae
Extinction is usually straight and uniform. The plagioclase is often weakly recrystallized although some adcumulate growth as defined by Wager, Brown, and Wadsworth (1960) is evident. Refractive index measurements via spindle stage techniques (Wilcox, 1959) were correlated to plagioclase composition (Slemmons, 1962). Estimated error based on the reliability of index oils in the range of plagioclase composition is ± An 4. The composition of plagioclase in the troctolite is An 88-92.

Olivine occurs as rounded or embayed grains with iddingsite and hematite along the fractures. It is biaxial positive with 2V = 86-90 indicating a composition of Fo 70-75. Wherever plagioclase and olivine are in close proximity a symplectic intergrowth of dark green spinel occurs with amphibole rimming the plagioclase grains and orthopyroxene rimming the olivine grains. The reaction does not occur when olivine is an inclusion in plagioclase. When interstitial amphibole is present it is in optical continuity with the amphibole produced in the olivine-plagioclase reaction.

Orthopyroxene occurs as poikilitic grains up to 10 cm in width. Locally orthopyroxene surrounds partially resorbed olivine. It is pleochroic from pink
to pale green, displays extinction parallel to (010), low interference colors and is biaxial positive with $2V = 78-80$. Optical properties indicate the composition is in the hypersthene series. The composition of the orthopyroxene that occurs in the plagioclase-olivine reaction could not be determined by optical properties.

Spinel occurs as a reaction product between olivine and plagioclase and as primary grains enclosed by olivine. Primary spinel is darker green than reaction-produced spinel. Opaques occur as interstitial masses and appear to be titaniferous magnetite.

**Plagioclase porphyry.** Plagioclase porphyry is exposed in a subelliptical zone on the southern tip of Viejas Mountain. The unit is named for the conspicuous plagioclase megacrysts that comprise up to 65% of the rock and range in size from 5 to 10 cm in length. The megacrysts of plagioclase impart a spotted appearance to the rocks and are visible for distances of several meters. Plagioclase is a cumulate phase and occurs as subhedral to euhedral grains with complex carlsbad, albite and deformed pericline twins. Overall the plagioclase has sutured boundaries with wavy, undulose extinction. It is often associated with olivine as small euhedral inclusions. Olivine is rare as inclusions
in plagioclase. Spindle stage techniques indicate the composition of plagioclase is An 86-90.

Olivine occurs as subhedral to anhedral grains with iddingsite and hematite along the fractures. It displays second-order yellow to red interference colors and is biaxial positive with $2V = 88-90$ indicating a composition of Fo72-75. Olivine is often enclosed by poikilitic amphibole, but more commonly by orthopyroxene. Where plagioclase and olivine are in close proximity there is often, but not always, a symplectic intergrowth of spinel as described earlier.

In some of the rocks in the plagioclase porphyry unit, amphibole occurs as anhedral poikilitic grains and uralite masses. It is pleochroic green to light brown and is fibrous with first-order interference colors. Extinction is usually inclined at 19-21. When amphibole is an interstitial phase, it is in optical continuity with the amphibole reaction rims on olivine and may invade plagioclase fractures. Uralite may comprise up to 5% of the rock in this unit. Where interstitial amphibole and uralite occur there is very little orthopyroxene present.

Orthopyroxene is an interstitial phase in most of the plagioclase porphyry unit. It occurs as anhedral to subhedral poikilitic grains up to 10 cm wide. It
is characterized by pink to light green pleochroism, first-order straw-yellow to grey interference colors, parallel extinction and is biaxial negative with 2V = 60-65. Optical properties indicate the composition is hypersthene. In the rocks with interstitial orthopyroxene the plagioclase does not display protoclastic texture as it does when uralite is abundant. Opaques occur as interstitial masses and as "wormy" intergrowths in the olivine.

**Two-pyroxene olivine gabbronorite.** Two-pyroxene olivine gabbronorite is exposed near the summit of Viejas Mountain and in an isolated pod near the northeast corner of the pluton. It is characterized by varying amounts of olivine, plagioclase and clinopyroxene with orthopyroxene as an interstitial phase. Textures are subequigranual to poikilitic and variations in the amount of mafic minerals result in a suite that ranges from melanocratic to leucocratic. Plagioclase is subhedral to euhedral with carlsbad, albite and few deformation twins. Extinction is usually straight and rarely wavy. It may partially enclose resorbed clinopyroxene grains. The composition is An 86-89.

Clinopyroxene forms subhedral to anhedral resorbed grains with clear to pale pink pleochroism.
It is biaxial positive with second-order blue interference colors, extinction inclined at 24°-26° and 2V = 45-50. Grain boundaries are always resorbed and often have sieve textures with amphibole of unknown composition filling the "holes." Optical properties indicate the clinopyroxene has the composition of diopside.

Olivine is subhedral to anhedral with hematite and iddingsite in the fractures. It is biaxial positive with second-order yellow to blue interference colors, straight extinction and 2V = 88-90 indicating the composition is Fo 72-75. Olivine is sometimes interstitial to plagioclase and clinopyroxene and often has rims of amphibole.

Orthopyroxene is an interstitial phase with pink to light green pleochroism. It is biaxial negative with first-order straw-yellow to grey interference colors and 2V = 52-55. It often encloses opaque minerals and overall encloses plagioclase, olivine and clinopyroxene. Optical properties indicate the composition is hypersthene. Amphibole occurs as rims around some olivine and the opaques occur as interstitial grains and wormy intergrowth in olivine and orthopyroxene.
Mafic dike. One analysis of a mafic dike collected in the plagioclase porphyry unit was completed. The rock is melanocratic, subequigranular and medium grained. The dike ranges from 1 cm to more than 20 cm in thickness. Plagioclase occurs as subhedral to euhedral aggregates with weak triple point textures caused by recrystallization. Twinning is usually scarce and is of the carlsbad, albite, and deformed pericline varieties. The composition of plagioclase is An 77-79.

Olivine forms subhedral rounded grains with hematite in the fractures. It is locally associated with dark green spinel and always surrounded by amphibole. It is biaxial positive with second-order green interference colors and 2V = 80-85 indicating a composition of Fo 65-70.

Orthopyroxene is anhedral with pleochroic pink to light green and an interstitial phase. It is biaxial positive with first-order straw-yellow to grey interference colors and 2V = 55-60. Optical properties indicate the orthopyroxene is in the hypersthene series.

Amphibole is the most conspicuous and most abundant phase. It occurs as stubby to prismatic, subhedral to euhedral aggregates with dark green to brown pleochroism and extinction inclined at 23-25. It is biaxial negative with second-order interference
colors and $2V = 85-90$. Locally it displays simple twins and is rarely interstitial. Some of the amphibole is uralitized and weakly recrystallized. Optical properties indicate the composition is in the hornblende series.

**Sequence of Crystallization in Group 1**

The cumulus phases in Group 1 are clinopyroxene, plagioclase and olivine, whereas orthopyroxene is an intercumulus phase. Plagioclase began to nucleate first followed by olivine and clinopyroxene. Orthopyroxene and lesser amphibole precipitated as the intercumulus phases. Opaques precipitated last and uralite developed as a deuteritic mineral.

**Group 2**

**Leuconorite.** Leuconorite is the most abundant rock type on Viejas Mountain and in Group 2. It is subdivided into two units based on mineralogic and textural parameters. Unit A is characterized by a population of plagioclase that is aligned subparallel to the prismatic orthopyroxene and has little or no interstitial material. Unit B has plagioclase that is characterized by a protoclastic texture and interstitial orthopyroxene. Plagioclase in Unit A is subhedral to euhedral, unzoned and displays carlsbad, albite and
pericline twins. Extinction is uniform to slightly wavy. Plagioclase in Unit B is crudely zoned, has wavy extinction and deformed twin lamellae and no planar fabric. The composition of plagioclase in both units is An 82-88.

Clinopyroxene occurs in variable amounts in both units of leuconorite but is most abundant in Unit B. It is subhedral to anhedral with a sieve texture. Some clinopyroxenes have simple twin lamellae. They are weakly pleochroic light pink to clear, display second-order blue to green interference colors and are biaxial positive with $2V = 45-50$ and extinction inclined at $30°-40°$. Amphibole of unknown composition fills the holes in clinopyroxenes with sieve textures. Optical properties of clinopyroxene indicate the composition is augite.

Orthopyroxene appears in both groups of leuconorite. In Unit A it is subhedral to euhedral and in subparallel alignment with plagioclase. In Unit B it is poikilitic and resorbed. It has first-order straw-yellow to grey interference colors, is biaxial negative with $2V = 60-65$ and has parallel extinction with pink to light green pleochroism. Optical properties of the orthopyroxene in Unit A and Unit B indicate the composition is in the hypersthene series.
Unit B contains minor amounts of interstitial amphibole. It is always associated with clinopyroxene in the sieve texture and as an interstitial phase. The interstitial amphibole is in optical continuity with the amphibole in the clinopyroxene "holes." It is biaxial negative, pleochroic light green to light brown, with $2V = 50-55$ and extinction inclined at $25^\circ-30^\circ$. Opaques occur as interstitial grains and may partially surround pyroxenes or occur as wormy intergrowths in the pyroxene.

**Hornblende gabbro.** One exposure of hornblende gabbro was found in the northeast corner of the map area (Plate I, back pocket). The gabbro is characterized by abundant amphibole and plagioclase. Plagioclase is subhedral to euhedral with albite, carlsbad and deformed pericline twins. Extinction is usually irregular and patchy andapatite inclusions are common. The plagioclase shows the effects of minor recrystallization along the grain boundaries and has an unzoned composition of An 71-74.

Amphibole forms clots of subhedral to euhedral crystals that are often moderately recrystallized. Pleochroism is dark green to pale brown and extinction is inclined at $15-20$ with second-order blue interference
colors. The amphibole is biaxial negative with $2V = 78-85$. Optical properties indicate that the amphibole is in the hornblende series. Opaques occur in the interstices between amphibole and plagioclase. Uralite is a common deuteric mineral.

Plagioclase was the first phase to nucleate and was followed by the precipitation of amphibole. Opaques were last to precipitate. Uralite developed finally as a deuteric mineral.
Chapter 3

STRUCTURE

Introduction

The gross internal structure of the Viejas Mountain Gabbro pluton is difficult to interpret. Everhart (1951) described the problems of structural study aptly when he wrote

The primary structures developed in the gabbro are so local and erratic in attitude and poorly exposed that it seems impossible to form from them an orderly or coherent pattern for even a single body. (Everhart, 1951, p. 100)

Although this observation seems applicable to Viejas at first glance, it is apparent that upon careful structural mapping the general internal structure of the pluton is definable.

The basic difficulty with studying the structure of the pluton is the fact that much of the exposed rock has been displaced downslope by gravity. Attitudes of igneous foliation vary dramatically from one exposure to the next. Many rock types are seemingly juxtaposed as a result of downslope movement of boulders. This section will discuss the structures seen within the pluton, the probable mechanisms that are responsible
for the development of the structures, and how the mechanisms pertain to the evolution of the pluton.

**Contact Relationships**

The contacts between the gabbroic rocks are drawn according to the first appearance of an individual rock type or mappable body. The author saw no contacts exposed within the pluton. However, the rock types are distinct mappable units within the pluton and no convincing evidence for gradational contact relationships was found.

The plagioclase porphyry unit is in sharp contact with leuconorite and troctolite. It contains inclusions of troctolite up to 8 feet long, troctolite locally contains 6-10" seams of plagioclase porphyry. These two rock types are confined to the southern tip of the pluton. With the exception of this area and two isolated pods of two-pyroxene olivine gabbronorite at the summit of Viejas Mountain and in the northeast section of the pluton the bulk of the pluton is comprised of leuconorite. Contact relationships between the leuconorite and the two-pyroxene olivine gabbronorite appear sharp.

Hornblende gabbro occurs as an isolated mass in the northeast corner of the map area and is in
probable contact with leuconorite to the west and tonalite to the east.

The gabbroic rocks are in contact with granitic units but the contact is never exposed. The slopes of Viejas are covered with colluvium which completely obscures the quartz diorite-gabbro contact.

**Mineral Layering**

Plagioclase, olivine, orthopyroxene and clinopyroxene are possible cumulate phases in the gabbroic rocks. Plagioclase always displays cumulate textures. Most of the rock types show evidence of adcumulus growth on plagioclase as defined by Wager, Brown, and Wadsworth (1960). Variations in the percent of mafic and felsic minerals result in a mineral layering in the leuconorite, and locally in troctolite. Plagioclase porphyry and gabbronorite do not display noticeable mineral layering. Wager and Brown (1967) discuss the origins and various types of mineral layering with reference to layered intrusions such as Skaegard, Rhum, Bushveld, etc. The mineral layering at Viejas Mountain is not as well developed nor as complete as the layering present in those stratiform bodies. Mineral layering is a function of density differences
in the cumulus mineral phases (Hess, 1960). Merriam (1946) discussed a process called "auto-injection" in which one liquid of different composition is injected into a host rock to result in a crude banding in the rocks. The seams of plagioclase porphyry in troctolite and abundant amphibole segregations in parts of the leuconorite are probably a result of this process.

Viejas Mountain gabbros never display mineral layers with monomineralic segregations. Orthopyroxene is the dominant mafic phase and plagioclase the dominant felsic phase. The most common type of layers are planar alternating light and dark bands about 4-10 inches thick. Locally they display cross bedding slump structures, and scarce graded bedding. The leuconorite may exhibit flow texture as defined by the parallel alignment of plagioclase and orthopyroxene.

Late-stage magmatic processes have resulted in the development of other planar features in the gabbroic rocks. Filter pressing effects are common in all of the units. The filter pressing process involves late stage fluids being squeezed into synplutonic fractures to develop thin (usually 1/2 inch) layers of mafic minerals, commonly amphibole. The filter press layers often exhibit synplutonic faults and chevron folds.
Comb structures are found in the plagioclase porphyry unit. They are always individual, never occurring in alternating layers. Moore and Lockwood (1970) discussed the origin of comb layers in the Sierra Nevadas and Walawender (1976) described a series of comb layers in the Los Pinos gabbro pluton in southern California. The comb structures at Viejas Mountain range from 6 cm to 30 cm in thickness. Plagioclase and amphibole are seen extending from a basal discontinuity which is in contact with the host rock which is usually a fine-grained mixture of plagioclase and amphibole. Amphibole blades become wider away from the basal discontinuity and are often up to 10 cm long and interfinger with tabular, less distinct plagioclase megacrysts.

Faults

One fault was mapped by the author in the northeast section of the map area (Plate I, back cover). The problem with mapping faults in the Viejas Mountain pluton as well as batholithic rocks in general (Larsen, 1948) is that fault gouge, mylonitization and fault breccia are rarely exposed. Viejas mountain shows no direct evidence for faulting.
Chapter 4

GEOCHEMISTRY

Introduction

Thirteen whole rock samples were analyzed for major and trace element geochemistry by the author. The rocks were analyzed with the Instrument Laboratories Spectrophotometer using atomic absorption and flame emission modes. Unknown samples were analyzed with U.S.G.S. standards, BCR-1, PCC-1, G-2, and AGV-1. Sample preparation followed the LiB\(_4\) fusion technique outlined by Suhr and Ingamells (1966).

Major Element Variations

The Viejas Mountain Gabbro pluton is generally high in Al\(_2\)O\(_3\) and CaO, and low in TiO\(_2\), K\(_2\)O, and total alkalis (Tables 2 and 3). Group 1 rocks are lower in SiO\(_2\), TiO\(_2\) and alkalis than Group 2. Variation diagrams are used to illustrate possible geochemical trends within the pluton and to emphasize the differences between Group 1 and Group 2 rocks. Fe and Mg commonly are indicators of differentiation because Mg is preferentially accepted into the early formed mineral
Table 2
Major and Trace Element Abundances of Group 1 Rocks

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<tr>
<th>Oxide</th>
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<sup>a</sup>Mafic Dike.

<sup>b</sup>Total Fe as Fe<sub>2</sub>O<sub>3</sub>.
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<td>&lt;10</td>
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<td>120</td>
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<sup>a</sup>Hornblende Gabbro.

<sup>b</sup>Tonalite.

<sup>c</sup>Total Fe as Fe<sub>2</sub>O<sub>3</sub>. 
phases with respect to Fe. Thus, as crystallization proceeds, the Fe/Mg ratio should increase in the residual melt and can be used as a measure of differentiation. Figure 2 shows a plot of Iron Index \( \frac{\Sigma Fe_2O_3}{\Sigma Fe_2O_3 + MgO} \) against Si\(O_2 \) and Na\(2O + K_2O \). Group 1 and Group 2 rocks define two distinct fields in each diagram. As the Iron Index increases the amount of Si\(O_2 \) and total alkalis roughly increase. Figure 3 is an AFM diagram showing the trend of the Viejas Mountain gabbros. The rocks show an iron enrichment trend in each group but with the Group 2 trend more alkalic than the Group 1 rocks.

**Trace Element Variations**

The gabbroic rocks were analyzed for the trace elements Cr, Ni, Sr, Rb, and V (Tables 2 and 3, pages 27 and 29). Trace element data is useful in the study of basic rocks because many trace elements are indicative of single mineral phases and can be used to support fractionation models. The trace element data shows that Group 1 rocks are higher in Cr, and slightly lower in Ni than Group 2 rocks.

To illustrate the trace element trends Cr and Ni are plotted against the Iron Index (Figure 4). The
Figure 2. Iron Index vs. SiO₂ and Total Alkalis.
Solid triangles = Group 1; open circles = Group 2;
open triangle = Mafic Dike.
Figure 3. AFM Diagram. Solid triangles = Group 1; open circles = Group 2; open triangle = Mafic Dike.
Figure 4. Iron Index vs. Ni and Cr (ppm). Solid triangles = Group 1; open circles = Group 2; open triangle = Mafic Dike.
plots of both Cr and Ni vs. Iron Index show a decrease as the Iron Index increases. Nishimori (1976) shows that in the olivine-rich rocks of the Peninsular Ranges gabbros, Cr is concentrated in the spinel phases and clinopyroxene. Clinopyroxene is generally lacking in Group 1 rocks. The Group 1 rocks (with clinopyroxene) have higher concentrations of Cr than do the Group 2 rocks.

Vanadium is generally low in olivine-rich rocks and increases in concentration as the abundance of pyroxene and amphibole increases (Wager and Mitchell, 1951; Nishimori, 1976). Figure 5 shows a plot of vanadium vs. Iron Index and TiO₂ vs. Iron Index. The diagram shows an increase in vanadium as the Iron Index increases. Vanadium is most abundant in the pyroxene-rich rocks of Group 2. Vanadium is characteristic of pyroxenes and iron ores and small amounts probably partition into plagioclase (Wager and Mitchell, 1951). Miyashiro and Shido (1975) state that vanadium, like titanium, is concentrated in magnetite and ilmenite. Group 2 rocks contain more opaques than Group 1 (Table 1, page 8) and have correspondingly higher values for vanadium and titanium. It is concluded, therefore, that those elements are concentrated in opaque minerals.
Figure 5. Iron Index vs. Vanadium (ppm) and TiO₂ (Wt. %). Solid triangles = Group 1; open circles = Group 2; open triangle = Mafic Dike.
Chapter 5

DISCUSSION

Interpretation of Petrography

Cumulate textures are common in basic igneous rocks. Wager, Brown, and Wadsworth (1960) described the processes that develop layered igneous rocks and the corresponding textures. They describe three types of igneous cumulates depending on the amount of interstitial (intercumulus) phases:

1. Orthocumulate: One or more cumulus minerals with an interstitial phase.
2. Mesocumulate: Interstitial phases are minor.
3. Adcumulate: No interstitial material.

Generally, the Peninsular Ranges gabbroic rocks have conspicuous amounts of interstitial material, thus making adcumulates scarce (Miller, 1938; Hoffman, 1976; Nishimori, 1976; Walawender, 1976, Lillis, 1978). The gabbroic rocks of Viejas Mountain lack abundant amphibole and the dominant interstitial phase is orthopyroxene. The Group 1 rocks are considered to be orthocumulates and mesocumulates, whereas Group 2 are mesocumulates.
Many of the rocks in both groups display evidence for recrystallization in that grain adjustments by pyroxene and plagioclase have led to triple-point textures. This texture could be confused with that formed by adcumulate growth.

Mineralogically, the two groups of gabbroic rocks are similar, but major differences occur in the textures. Plagioclase, olivine, clinopyroxene and orthopyroxene may be cumulate phases. If olivine is not present (as in Group 2), orthopyroxene (or clinopyroxene) is the first mafic phase to nucleate. Plagioclase usually begins crystallization before olivine and pyroxene. The plagioclase in Group 1 and Group 2 rocks has a limited range in composition (Table 1, page 8). The presence of cumulus olivine in Group 1 and resorbed clinopyroxene in Group 2 defines a mineralogic distinction between the two groups. Group 1 is considered older than Group 2 and thought to represent a less fractionated intrusion from a common parent melt. The attitude of mineral layering indicates the pluton has a crude basinal shape with the Group 1 rocks occupying the lower elevations (Plate I, back pocket). The above characteristics of the pluton do not indicate that the pluton crystallized as a single differentiating magma as in layered igneous intrusions elsewhere (Wager and
Brown, 1967; Best and Mercey, 1967; Nishimori, 1976). The pluton is similar to the Los Pinos gabbro pluton (Walawender, 1976) in that it formed as the result of more than one pulse of magma from a common parent melt.

One of the most conspicuous aspects of the petrography of the Viejas Mountain pluton is the calcic plagioclase. Miller (1937) suggested that a calcic magma was required to crystallize anorthite. More recent work has shown that anorthite may crystallize from a basaltic or andesitic magma under conditions of elevated water pressure (Yoder, 1969). The presence of megacrysts of anorthite in Group 1 and the calcic plagioclase in Group 2 suggests that the parent melt may have crystallized under conditions of elevated water pressure.

Olivine is only found in Group 1 rocks. Olivine is unzoned and ranges in composition from Fo 70-85. Nishimori (1976) reports one olivine analysis from Viejas Mountain with a composition of Fo 70. That olivine analysis also shows that it is lower in MnO and SiO₂ and higher in FeO than olivines from Guatay Mountain and North Peak. The composition of olivine from Viejas is similar to the range of compositions found in high-alumina basalts and basaltic andesites (Best, 1969).
Best (1969) also observed a correlation between the coexisting anorthite content of plagioclase and forsterite content of olivine in calc-alkaline rocks in that phenocrysts of calcic plagioclase and olivine in the range Fo 70-84 often coexist in calc-alkaline magmas and calc-alkaline plutons. However, in "dry" basic intrusions such as the Skaergar similar olivine ranges coexist with less calcic plagioclase (Wager and Brown, 1967). Coexisting forsteritic olivine and calcic plagioclase again, suggest crystallization under conditions of elevated water pressure.

Clinopyroxene occurs in Group 1 and Group 2 rocks. In Group 1 the composition is diopside and it is seen in only one rock type within the group. In Group 2 the composition is augite. In many basalts the first pyroxenes to crystallize are diopside, but as crystallization proceeds, the composition becomes less calcic and the pyroxenes shift to the augite variety (Deer, Howie, and Zussman, 1971). Kuno (1960) observed that high-alumina basalts often have more calcic clinopyroxenes than tholeiitic basalts. Le Bas (1962) noted that the high-calcium clinopyroxenes may be related to high-alumina basalt or calc-alkaline magmas. Clinopyroxene will crystallize on the liquidus in a high-alumina basalt melt at pressures greater than 5kb. At
lower pressures olivine and plagioclase replace clinopyroxene on the liquidus (Kushiro and Thompson, 1972; Thompson, 1974, 1975). All of the clinopyroxenes in both groups display resorbed euhedral shapes and sieve texture suggesting that they crystallized early.

Many authors have discussed the reaction between olivine and plagioclase. Most conclude that the reaction is a subsolidus, high-temperature retrograde metamorphic reaction (Shand, 1945; Murthy, 1958; Froedesen, 1968). The reaction observed in Group 1 rocks is:

\[
\text{Olivine} + \text{Plagioclase} + H_2O \rightarrow \text{Amphibole} + \text{Spinel} + \text{Orthopyroxene}
\]

Locally the amphibole product is in optical continuity with interstitial amphibole, but interstitial amphibole is scarce. Walawender (1976) described similar reactions in the Los Pinos gabbro. Hoffman (1976) and Lillis (1978) report similar reactions in the Lawson Peak Orbicular gabbro and Corte Madera gabbro, respectively, but as in the Los Pinos gabbro, these plutons contain conspicuous amounts of amphibole as an interstitial phase. The presence of small amounts of interstitial amphibole in optical continuity with reaction produced amphibole suggests that the reaction occurred in the presence of a volatile bearing melt as also suggested
by Walawender (1976). Yoder (1969) reported that the olivine-plagioclase reaction will produce spinel and clinopyroxene at pressures as low as 2 kb if water excess conditions exist.

Plagioclase in Group 1 and Group 2 often displays deformation twinning and protoclastic textures. Locally the leuconorites have pronounced parallel alignment of plagioclase crystals. Where this occurs the plagioclase is not deformed and extinction is straight. Spry (1969) attributes deformation as the cause of pericline twins and curved, wedge-shaped polysynthetic twins. Protoclastic textures are confined to the grain boundaries. The protoclastic texture is the result of granulation of crystals during crystallization (Spry, 1969) or postdepositional mechanical adjustments between grains (Nishimori, 1976). Hoggat and Todd (1977) suggested that the gabbroic rocks were effected by a regional metamorphic event during and after emplacement. However, Berggreen and Walawender (1977) state that metamorphism of a roof pendant in the batholith occurred prior to the emplacement of the gabbroic plutons but may have continued slightly beyond the emplacement episode. Although the rocks of both groups often display minor amounts of recrystallization, it is not likely they were effected by a major regionally metamorphic
event after emplacement because there is no evidence of regional metamorphic features. Postdepositional mechanical adjustments of the crystal mush probably caused the deformation twins and protoclastic textures.

The comb structures found in Group 1 rocks represent water-rich fluids that were recrystallized in fractures allowing for the nucleation of large crystals of plagioclase and amphibole. Poldervart and Taubenuck (1958) discuss the origin of similar comb structures in the Willow Lake area.

**Interpretation of Geochemistry**

The Viejas Mountain Gabbroic pluton is one in a series of basic plutons exposed in the western portion of the Peninsular Ranges batholith. The petrographic and geochemical characteristics of the pluton show the rocks are similar to other gabbroic plutons in the batholith. It appears that all of the gabbroic plutons are genetically related. Several authors have provided geochemical data relating to the Peninsular Ranges gabbro plutons. Larsen (1948) and Larsen and Draisen (1951) published numerous analyses of gabbroic rocks and minerals, respectively, but did not evaluate a single pluton. Nockolds and Allen (1953), and Sen, Nockolds,
and Allen (1959) studied trace element and major element abundances in gabbroic rocks of the batholith and discussed trace element trends in the individual mineral phases. Alberede (1976) used rare earth element patterns to argue that the Peninsular Ranges gabbros were differentiates of a parental tonalite magma. Nishimori (1976) suggests that the Peninsular Ranges gabbros are the refractory residua of a calc-alkaline system that produced the batholith. He suggests that the parent magma was high-alumina basalt to basaltic andesite. Hoffman (1976) did not publish geochemical data, but his petrographic data imply that the Lawson Peak gabbro had a high-alumina basalt parent. Walandwender (1976) and Lillis (1978) suggested the parent magma for the Los Pinos and Corte Madera gabbros, respectively, were high-alumina basalt. Considering the petrographic and geochemical similarities between Viejas Mountain and the above-mentioned plutons the parent magma of the Viejas gabbro is suggested to be hydrous high-alumina basalt.

The major element and trace element geochemistry, coupled with petrographic and structural data, imply that the Viejas Mountain gabbros were subject to a process of fractional crystallization. Group 1 rocks are more basic than Group 2 and have lower values for \( \text{SiO}_2 \), \( \text{TiO}_2 \).
and higher values for Cr and Ni concentrations. Silica content is not necessarily a reliable determinant of the fractional crystallization process. The abundance of SiO$_2$ relative to the other elements in the Viejas Mountain gabbros requires an unlikely correlation between SiO$_2$ and the other oxides. Thus, using SiO$_2$ as an indicator of fractional crystallization from variation diagrams is not accurate because there are many possible processes involved in the variation between the rocks of a given group (Chayes, 1964). TiO$_2$, as well as Cr and Ni, are valuable indicators of the fractional crystallization process. Wager and Mitchell (1951), and Miyashiro and Shido (1975) show that TiO$_2$ is incorporated into magnetite and ilmenite in the fractionation process. Since magnetite is not an early phase at Viejas, the TiO$_2$ values tend to increase as the rocks become more fractionated, i.e., go to higher Fe/Mg ratios (Tables 2 and 3, pages 27 and 29).

The most obvious distinction between Group 1 and Group 2 is in Iron Index and total alkalis (Figures 2 and 3, pages 32 and 33). If fractional crystallization is the dominant process that produced the two groups, it should be evident in the above diagrams. The Iron Index should increase as MgO is removed from
the melt with the crystallization of the mafic phases
clinopyroxene and olivine and alkalis should correspond-
ingly increase. This relationship is evident in the
above diagrams which show that Group 1 is less fraction-
ated than the rocks of Group 2 due to the removal of Fe
and Mg from the melt and subsequent increases in Na and
K.

**Petrogenetic Model**

There are perhaps as many petrogenetic models
for the occurrence of cumulate gabbros as there are
gabbroic plutons. Nishimori (1976) exhaustively
reviewed the most recent data on this topic and the
reader is referred to his work for details. Nishimori
attempted to present a viable mechanism for the evolu-
tion of the Peninsular Ranges gabbros and calc-alkaline
rocks of the batholith. He proposed that the gabbros
are the refractory residua of a calc-alkaline differ-
entiation trend from a high-alumina basalt to baslatic-
andesite magma. Walawender (1976) utilized the
experimental work of Kushiro and Thompson (1972) to
formulate a model for the emplacement of the Los Pinos
gabbro. Starting with a parent melt of high-alumina
basalt, the experimental studies showed that clino-
pyroxene is the liquidus phase at greater than 5kb
pressure. Plagioclase and olivine are liquidus phases at less than 5kb. Mullen and Bussel (1977) conclude that the Cordilleran gabbros were emplaced between 1.5 and 5kb. Walawender (1976) suggests the Los Pinos gabbro pluton was emplaced between 2-3kb.

A high-alumina basalt melt was produced during Jurassic time by partial melting of the lithosphere along a Benioff Zone (Gastil, 1975). The magma rose along the Benioff Zone where it was probably separated into more than one magma chamber. Plagioclase and olivine precipitated from the initial melt to form the rocks of Group 1. The residual magma, being somewhat depleted in Fe and Mg, rose to the level of Group 1 rocks where plagioclase and orthopyroxene nucleated to form the rocks of Group 2. The crystal mush was subjected to convective overturn and filter pressing to produce the rhythmic layering and igneous structures described. The emplacement of Group 2, in effect, completed the development of the pluton and probably caused the recrystallization fabric and protoclastic and deformation twins to develop in the plagioclase.


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ABSTRACT
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The Viejas Mountain Gabbro pluton is located about 2 km northeast of Alpine, San Diego County, California, and is one in a series of gabbroic plutons in the Peninsular Ranges batholith. The rocks of the pluton are divided into two groups. Group 1 consists of troctolite, plagioclase porphyry, and two-pyroxene olivine gabbronorite and Group 2 consists of two units of leuconorite plus hornblende gabbro. Group 1 has plagioclase and olivine as cumulus minerals, whereas Group 2 has plagioclase and orthopyroxene as the cumulus phases. Clinopyroxene is a cumulus phase in Group 2 and rarely in Group 1. The rocks display mineral layering, comb structures, and local flow banding. Overall, the pluton has a crude basinal shape with all of the rocks dipping inward. Geochemical analyses show that a process of fractional crystallization from a cogenetic parent melt produced the two groups of gabbro. Group 1 is less fractionated than Group 2 and has correspondingly lower values for the Iron Index ($\Sigma Fe_2O_3/\Sigma Fe_2O_3 + MgO$) and lower values for total alkalis. Each group displays a general iron enrichment trend. The petrographic and geochemical information suggests
the rocks had a parent magma of hydrous high-alumina basalt that began crystallizing at greater than 5kb pressure and was emplaced in a series of pulses to produce the relationships between Group 1 and Group 2 at their present erosional level.
PLATE 1: GEOLOGIC MAP OF THE VIEJAS MOUNTAIN GABBROIC PLUTON, ALPINE, CALIFORNIA

EXPLANATION

QG COLLOVISUM
QAL ALLUVIUM

GRANITIC ROCKS
KA ADAMELLITE
KUD UNDIVIDED TONALITE AND DIORITE

GABBROIC ROCKS
KHG HORNBLENDE GABBRO
KLN LEUCONORITE
KOQ TWO-PYROXENE OLIVINE GABBRO-NORITE
KF PLAGIOCLASE PORPHYRY
KT TROCTOLITE

SYMBOLS

GEOLOGIC CONTACT
DASHED WHERE APPROXIMATE
DOTTED WHERE INFERRED

STRIKE AND DIP OF FOLIATION

SCHLIEREN ZONE

LANDSLIDE DIRECTION

SAMPLE LOCATION POINT

SECTION CORNER

FAULT

SCALE
0 1 2 MILES
0 1 2 KM

CALIFORNIA

GEOLOGY, PETROLOGY, AND GEOCHEMISTRY OF THE VIEJAS MOUNTAIN GABBROIC PLUTON RICHARD J. ALLINGER 1978