The origin of the Wilson Ridge pluton and its enclaves, northwestern Arizona: Implications for the generation of a calc-alkaline intermediate pluton in an extensional environment

Lance Louis Larsen

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The origin of the Wilson Ridge pluton and its enclaves, northwestern Arizona: Implications for the generation of a calc-alkaline intermediate pluton in an extensional environment

Larsen, Lance Louis, M.S.

University of Nevada, Las Vegas, 1989
THE ORIGIN OF THE WILSON RIDGE PLUTON AND ITS ENCLAVES, NORTHWESTERN ARIZONA: IMPLICATIONS FOR THE GENERATION OF A CALC-ALKALINE INTERMEDIATE PLUTON IN AN EXTENSIONAL ENVIRONMENT

By

Lance L. Larsen

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Geology

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University of Nevada, Las Vegas
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ABSTRACT

The Wilson Ridge pluton is an epizonal calc-alkaline pluton that formed about 13.5 Ma during a period of mid-Miocene extension. The pluton was passively emplaced into a 1.7 to 1.8 Ga Precambrian crystalline terrain. High-angle normal faulting resulted in a series of horsts and grabens that provide windows into deep structural levels of the pluton. The apex of the pluton, in the Boulder Wash area, Nevada, is composed of hypabyssal quartz monzonite and dacite. The base of the pluton is 20 kilometers to the south where quartz monzodiorite, monzodiorite, and diorite are in low-angle intrusive contact with Precambrian basement. The pluton was separated from cogenetic volcanic rocks in the River Mountains by movement along the Saddle Island detachment fault at about 13 Ma. The River Mountains now lie 20 kilometers west of the pluton.

The Wilson Ridge pluton is composed of the Teakettle Pass suite, comprised of foliated monzodiorite and quartz monzodiorite, and unfoliated quartz monzonite; and the older Horsethief Canyon diorite. Rocks of both suites contain 0.5 to 4 modal percent sphene.

Intermediate rocks of the Teakettle Pass suite contain abundant basalt and diorite enclaves. Basalt enclaves are lensoidal and pillow-like and commonly have crenulate and fine-grained margins. Enclaves are chemically similar to mafic dikes of the Wilson Ridge pluton and to cogenetic alkali basalt flows in the River Mountains. They probably represent blobs of mafic liquid that commingled and
mechanically mixed with felsic magma to produce intermediate rocks of the Teakettle Pass suite. Basalt enclaves commonly occur as inclusion-rich zones that represent synplutonic mafic dikes that were injected into a quartz monzonite host. Mafic magma was entrained and mechanically broken down by magmatic flow shear.

Field evidence and major and trace element models suggests that the intermediate rocks of the pluton were produced by the commingling of a large volume of mafic magma with a smaller volume of felsic magma (a mafic-felsic ratio of about 70:30) as well as fractional crystallization. Similar open system processes may be responsible for the production of calc-alkaline intermediate rocks in other parts of the Great Basin.
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INTRODUCTION

Location and Geography

The Wilson Ridge pluton forms part of the northern Black Mountains in northwestern Mohave County, Arizona and southern Clark County, Nevada. Most of the pluton lies within the Lake Mead National Recreation Area (Figure 1). The thesis area covers 72 km² and includes the southern part of the Wilson Ridge pluton (Figure 2). It extends from latitude 35° 57' 30" to 36° 02' 30" north, and longitude 114° 35' 00" to 114° 42' 00" west, and includes parts of the Hoover Dam, Petroglyph Wash, Ringbolt Rapids, and Mount Wilson (temporary sheet) 7½ minute quadrangles. Access to the pluton is limited to unimproved dirt roads that are maintained by the National Park Service. These roads include the Kingman Wash, White Rock Canyon, Horsethief Canyon, Two B's Mine, and the Wildhorse Spring roads.

Previous Work

The Wilson Ridge pluton was originally described as a Precambrian gabbro to granite pluton that locally intrudes greenschist and amphibolite grade metamorphic basement rocks (Longwell, 1936). In the Boulder Canyon area, Longwell described a small hornblende gabbro pluton that was intruded by biotite granodiorite. These intrusive rocks in Boulder Canyon are now beneath the waters of Lake Mead. Longwell later mapped the northern Black Mountains south of Lake Mead as Precambrian basement locally intruded by Tertiary
FIGURE 1. Location of study area (modified from Feuerbach, 1986).
FIGURE 2. Index map of the Colorado River trough and Lake Mead region showing the Wilson Ridge pluton, associated volcanic section in the River Mountains, and other Tertiary plutons. Stippled patterns are Tertiary plutons. Area shown on figure 3 is outlined by the box.
granite, granodiorite and diorite (Longwell, 1963). He also recognized the high-angle normal faults that bound the Wilson Ridge horst, including the Indian Canyon, Emery, Ransome, and Fortification faults (Plate 1) (Longwell, 1963).

Anderson et al. (1972) provided K-Ar biotite dates of 15.1 ±0.6 Ma for granite and 13.6 ±0.6 Ma for quartz monzonite of the Wilson Ridge pluton. Anderson (1978) mapped the contact of the pluton with the Precambrian basement and noted a moderately strong mesoscopic foliation within intrusive phases. Near the southern margin of the pluton this foliation is locally coplanar with foliation in basement rocks.

Mills (1985) mapped the Hoover Dam 15' quadrangle which includes the western part of the Wilson Ridge pluton. He described plutonic rocks of the Wilson Ridge pluton that range in composition from diorite to granite with textures varying from hypabyssal to coarse-grained.

Feuerbach (1986) provided a detailed map of the northern Wilson Ridge pluton (south of Lake Mead) and a reconnaissance map of its southern part, and described many of the low-angle and high-angle normal faults that cut the pluton. He mapped a coarse-grained diorite and monzodiorite to pegmatitic diorite pluton in the southwestern part of the Wilson Ridge. Feuerbach also demonstrated that diorite was intruded by the more felsic phases of the Wilson Ridge pluton.

Naumann (1987) mapped and described the hypabyssal and volcanic phases in the apex of the pluton in the Boulder Wash area of southern Nevada. He described mesoscopic and microscopic liquid-liquid mixing textures and disequilibrium mineral assemblages in intermediate composition plutonic rocks of
the Wilson Ridge pluton and basaltic-andesite to dacite flows of the Boulder Wash volcano. Naumann (1987) was the first to suggest that magma commingling was an important process in generating calc-alkaline intermediate rocks of the Wilson Ridge pluton and cogenetic volcanic suites.

**Purpose**

The objectives of this study were to:

1. Identify intrusive phases of the southern part of the Wilson Ridge pluton by detailed field mapping.
2. Lithologically and chemically describe the igneous rocks of the southern part of the Wilson Ridge pluton by thin section analysis and major and trace element geochemistry.
3. Determine the origin of mafic enclaves within intermediate phases of the Wilson Ridge pluton.
4. Model the petrogenesis of the rocks of the pluton. The importance of open-system magmatic processes including assimilation and fractional crystallization was also evaluated.
5. Suggest possible models for the mode of emplacement of the pluton(s).

**Regional Setting**

In the Lake Mead area of southern Nevada and northwestern Arizona, igneous rocks produced during a period of mid-Tertiary extension (18 to 9 Ma) are mainly calc-alkalic or alkali-calcic with basaltic-andesite, andesite, and dacite predominating in volcanic suites and diorite to quartz monzonite in plutonic suites. Basalt and minor amounts of rhyolite erupted after extension (post 9 Ma)
but these rock types are rarely observed in the older (18 to 9 Ma) stratigraphic record (Smith et al., 1989). This pattern of extension-related intermediate volcanism followed by post-extension basaltic volcanism is recognized in many areas of the Great Basin (for example Anderson, 1973; Elston and Bornhorst, 1979; Eaton, 1982; Otton, 1982; Smith, 1982; Glazner, 1989; Glazner and Ussier, 1989). Bimodal volcanism occurred, however, locally during Tertiary extension (McKee, 1971; Lipman et al., 1972; Suneson and Lucchitta, 1983). The change in the nature of volcanism from calc-alkaline/alkali-calcic to basaltic in the Great Basin and the adjacent Colorado Plateau has been attributed to crustal cooling (Damon, 1971), to changes in the structural "state" of the crust (Smith et al., 1989) and to a progressive change in crustal density (Glazner and Ussier, 1989).

Processes proposed for the generation of intermediate igneous rocks during regional extension include assimilation of crustal material during the ascent of mafic magma from a mantle source (Damon, 1971), mixing of felsic and mafic magmas (Glazner, 1989), and complex open-system processes involving assimilation and/or mixing of a felsic component with a fractionated mafic phase (Nielson and Dungan, 1985; McMillan and Dungan, 1986; Novak and Bacon, 1986; Smith et al., 1989). A common theme in all of these models is the interaction of mafic and felsic components to produce rocks of intermediate composition. Basalt and rhyolite (the end members) erupt following extension when hybridization processes are no longer effective. In many areas of the southern Great Basin, studies of intermediate rocks of Tertiary age involve mainly volcanic assemblages, because Tertiary plutons are rarely exposed or are poorly
studied. An exception is the Colorado River trough, where structural and topographic relief provide excellent exposures of Tertiary plutons and cogenetic volcanic rocks. Although few studies have been completed on the plutons of the Colorado River trough, available field and geochemical data indicate that they are intermediate in composition and formed just prior to or during extension. Plutons (Figure 2) include the Newberry (Mathis, 1982; Volborth, 1964); Nelson (Anderson, 1972); Mt. Perkins (Faulds, et al., 1988); Searchlight (Paul Proctor, unpublished map); Boulder City (Anderson, 1969) and Wilson Ridge (Anderson, 1972; Feuerbach, 1987; Naumann, 1987; Smith et al., 1989).

The Wilson Ridge pluton is the largest and the northernmost of these plutons, and locally contains abundant mafic enclaves. The enclaves vary in composition from basalt to diorite and range from angular blocks and pillow-like blobs to phacoidal and fusiform enclaves that grade into mafic schlieren. Naumann (1987) described and recognized the significance of the enclaves and disequilibrium mineral assemblages in hypabyssal quartz monzonite in the northern part (the apex) of the pluton.

**STRUCTURAL GEOLOGY**

**Introduction**

The Wilson Ridge pluton is an epizonal and hypabyssal intrusion that is cut by numerous north-northwest trending, high-angle normal faults and low-angle normal faults. High-angle block faulting produced a series of horsts and grabens that expose different structural levels of the pluton (Feuerbach, 1986). Low-angle normal faults near the southwestern margin of the pluton are cut by high-angle
faults. Both low and high-angle normal faults show down-to-the-west displacement. On the other hand, high-angle normal faults on the eastern margin of the pluton show down-to-the-east displacement (Figure 3). Field relationships suggest that high-angle faulting occurred after low-angle faulting. This relationship is observed in other parts of the Lake Mead area (Weber and Smith, 1987; Smith, et al., 1989; Duebendorfer et al., 1989).

**Description of Faults, Mineralization, and Dikes**

The western range-bounding fault of the Wilson Ridge horst (Indian Canyon fault, Plate 1) juxtaposes coarse-grained quartz monzonite in the footwall against fine-grained to hypabyssal quartz monzonite in the hanging wall. At least 3100 feet of vertical separation occurs across the Indian Canyon fault, as evidenced by the displacement of a fine-grained quartz monzonite from 2500 feet elevation west of the fault to an elevation of 5600 feet east of the fault.

Detailed field mapping by Feuerbach (1986), Naumann (1987) and Larsen (this study) indicate that the entire pluton has been moderately tilted (≈5°) to the north. This suggests that high-angle range-bounding faults may be scissor faults, with greater displacement along the southern margin of the pluton than along the northern margins of the pluton.

Many fault surfaces are highly polished and show excellent slickensides. A few faults contain elongate riebeckite (sodium amphibole) crystals that have grown parallel to slickensides, implying that mineral growth along some surfaces
FIGURE 3. Geologic map of the central and southern Wilson Ridge pluton. Area of map shown on figure 2.
was synchronous with movement along the fault. Rocks of the Teakettle Pass suite were locally affected by potassium metasomatism. Potassium metasomatism commonly resulted in the addition of K (up to 12%) and the expulsion of Na (< 0.1%). Crystallization of riebeckite may have been in response to transport and deposition of Na along fault surfaces and other fractures. Na was probably expelled from quartz monzonite during K metasomatism. The occurrence of riebeckite as a coating on fractures is rare (Deer et al. 1972).

Many of the major high-angle faults on both the western and eastern margins of the pluton exhibit mineralized breccia zones. These zones are 1 to 20 m wide, are typically dark red-brown, and contain very large (2-10 cm) crystals of barite. Barite is chalky white, blade-shaped, and is set in a fine-grained matrix of hematite, and minor drusy quartz. Mineralized breccia zones typically consist of several synthetic and antithetic faults showing normal movement. Rocks in these zones show extreme brecciation and cataclastic deformation. This type of deformation is indicative of relatively shallow crustal levels (Sibson, 1977).

Reconnaissance mapping south of the Wilson Ridge pluton, north of Householder Pass, and east of Two B’s Mine revealed a sub-horizontal mylonite zone in the Precambrian gneisses. The magnitude, age, and sense of shear of this fault were not determined.

Dike emplacement was coeval with both high-angle and low-angle faulting. Dikes vary in composition from granite, granite porphyry, aplite, andesite, basalt, and biotite lamprophyre and are coplanar with the north-striking high-angle normal faults. Dikes are tabular and range in thickness from 0.5 to 30 m.
Feuerbach (1986) estimated that at least 400 north-trending dikes with an average width of 7 m intruded the core of the pluton and accommodated approximately 20% east-west extension.

**Structural Setting**

Geochemical correlations suggest that the pluton is the subvolcanic equivalent of volcanic rocks in the River Mountains (Weber and Smith, 1987). The River Mountains now lie 20 km west of the pluton and were probably separated from it by movement along the Saddle Island detachment fault at about 13 Ma (Figure 4) (Weber and Smith 1987; Duebendorfer et al., 1989). The cogenetic relationship between the Wilson Ridge pluton and the River Mountains is strengthened by evidence presented here that demonstrates chemical affinities between mafic enclaves and dikes of the Wilson Ridge pluton, and alkali basalt flows in the northern River Mountains.

Paleomagnetic studies indicate that the pluton was not appreciably tilted to either the west or east during faulting (Faulds et al., 1988). However, a gentle northward rotation ($\approx 5^\circ$) and deep erosion provide a cross section of the pluton in map view (Figure 4) (Feuerbach, 1986). This gentle northward rotation is based on detailed field mapping by Feuerbach (1986), Naumann (1987), and Larsen (this study) that shows that the volcanic and hypabyssal phases of the pluton are exposed in the northern part of the pluton, and deeper structural levels are exposed to the south. The hypabyssal cap of the pluton is in the Boulder Wash area, Nevada (Naumann, 1987) and the base is exposed nearly 22 kilometers to
FIGURE 4. Simplified geologic map of the Wilson Ridge pluton and adjacent areas of the Lake Mead area. The apex of the Wilson Ridge pluton is located in the Boulder Wash area and the base is 20 kilometers south near Horsethief Canyon (HC). SI is the Saddle Island detachment fault.
the south in northwestern Arizona where the pluton is in low-angle intrusive contact with the Precambrian basement.

**PRECAMBRIAN METAMORPHIC ROCKS**

**Introduction**

Precambrian crystalline rocks are exposed in the central and southern part of the Black Mountains. Precambrian rocks of the Black Mountains have not been dated, although they may be correlative with other Precambrian rocks exposed in northwestern Arizona dated at about 1.7 Ga (U-Pb zircon) (Karlstrom et al., 1987, Figure 2). The contact between plutonic rocks of the Wilson Ridge pluton and the heterogeneous Precambrian basement rocks is a sharp, intrusive contact that dips gently (≤30°) to the south-southwest. This contact is commonly digitate with small localized injections of felsic igneous rocks into crystalline basement (Figure 5).

**Description of Precambrian Rocks**

Metamorphic rocks in direct contact with plutonic rocks of the Teakettle Pass suite of the Wilson Ridge pluton are typically quartzofeldspathic (granitic) gneiss, amphibolite, and minor amounts of biotite and chlorite schist. Gneiss is the dominant Precambrian lithology in the central Black Mountains and form a monotonous sequence more than 800 m thick. Granitic gneiss is composed of quartz, orthoclase, plagioclase, biotite, minor amphibole, almandine garnet, and hematite (Appendix A). Orthoclase locally occurs as large augen (0.5 to 3 cm). Gneisses are banded with individual felsic and mafic domains ranging from 2 mm
FIGURE 5. Photograph shows digitate, intrusive contact between Precambrian gneiss (PCg) and Tertiary intrusive rocks (Teakettle Pass suite monzodiorite, Tmd).
to 30 mm in width. Some felsic domains are anastomosing and appear to cross
the dominant metamorphic foliation that is defined by banding in gneisses. This
foliation strikes west-northwest and dips gently to the south-southwest (Figure 6).

Another important Precambrian lithology is hornblende plagioclase
amphibolite that occurs as numerous concordant and discordant tabular bodies of
small pods. Amphibolite shows a strong metamorphic fabric defined by lineated
subhedral to euhedral hornblende needles and subhedral plagioclase laths.
Plagioclase crystals show minor alteration to epidote and sericite.

A small block of garnet-bearing quartzofeldspathic gneiss crops out 1.5 km
west of Horsethief Canyon. Garnets occur only locally, compose less than 5% of
the rock, and are nearly completely retrograded to chlorite. In hand sample they
are dark red-brown anhedral to subhedral crystals (1 to 3 mm).

In White Rock Canyon there is a wide (5 to 10 m) pegmatite dike that is
composed of coarse-grained granophyric quartz and orthoclase with large (2 to 6
cm) books of subhedral to euhedral black to brassy biotite, and minor amounts of
hematite. Similar Precambrian pegmatite dikes (30 to 40 m wide) are exposed as
resistent ridge-forming bodies throughout the central and southern Black
Mountains.

Small blocks of Precambrian basement occur within the pluton. Some
pendants may be large stoped blocks that foundered into the magma chamber.
Other blocks represent roof pendants. For example, a large (500 m long and 250
m wide) granitoid gneiss roof pendant crops out 1 km east of Mount Wilson.
Although most roof pendants are composed of banded gneisses, two small
FIGURE 6. Equal-area lower hemisphere projection of poles to planes of foliation for Precambrian metamorphic rocks.
(<125 m²) pendants in Horsethief Canyon (Figure 3) are olivine gabbro. Olivine gabbro is medium to coarse-grained, poikilitic and granular with high-angle grain boundary contacts. These rocks are massive with a very high specific gravity (>3.0 gm/cm³), and show no evidence of strain. They are composed of clinopyroxene, orthopyroxene, plagioclase, olivine, biotite, secondary chlorite, secondary fibrous actinolite and tremolite, and minor amounts of magnetite. Small (<2mm) euhedral polysynthetically twinned plagioclase laths are enclosed in orthopyroxene crystals (ophitic texture). Small pods of similar olivine gabbro also crop out in the metamorphic basement south of the pluton (Figure 3) and are in fault contact with Precambrian gneisses and pegmatites.

**Protoliths**

The relative homogeneity of the thick (>800 m) sequence of granitic gneiss and the lack of intercalated metasedimentary lithologies such as pelitic schist, psammite, or marble suggests an igneous protolith for the granitic gneiss. They may represent amphibolite grade metamorphism of a granitoid intrusion or a thick stack of felsic volcanic rocks.

Mineral textures and outcrop geometries of amphibolites suggests that they may have mafic igneous protoliths, and may represent small stock-like gabbroic intrusions. Tabular bodies of amphibolite possibly represent diabase or basalt dikes and sills.

Olivine gabbros are mafic igneous rocks and are possibly cumulates. The age and origin of these rocks is problematic. The petrologic relationship between olivine gabbro and the Wilson Ridge pluton or Precambrian metamorphic rocks is
unknown.

**Post-Wilson Ridge Sedimentary Rocks**

Clastic sedimentary rocks crop out on the eastern and western flanks of Wilson Ridge. The oldest of these sedimentary units is the Tertiary Muddy Creek Formation which is composed of moderately well-indurated conglomerates and coarse sandstones. Most conglomerates are clast supported, although some are matrix supported. Clasts are subangular to angular, poorly sorted, and range in size from 1 to 30 cm. Common clast lithologies include Precambrian metamorphic rocks, porphyritic andesite and dacite (possibly Patsy Mine Volcanics and dike rocks of the Wilson Ridge pluton), and Wilson Ridge pluton intrusive rocks. Individual beds commonly show one dominant clast lithology. Clasts in matrix supported conglomerates are set in a red-brown silty-sand matrix.

Sandstone is interbedded with conglomerates and is coarse-grained (1 to 2 mm) and poorly sorted. Individual sandstone beds are 3 to 10 cm thick and are commonly channelized and lenticular. Some beds are normally graded. Grains are predominantly quartz, plagioclase, orthoclase, and minor hornblende and biotite, and are set in a silty-clay matrix.

Locally capping clastic rocks of the Muddy Creek Formation are olivine-alkali basalt flows of Fortification Hill. Fortification Hill basalts are dated at between 4.7 and 5.88 Ma (Smith et al., 1989).

Disconformably overlying conglomerates and sandstones of the Muddy Creek Formation are poorly indurated conglomerates of Quaternary (?) age. These conglomerates are grey in color and are generally less than 2 m thick.
They are clast to matrix supported with a fine silt to sand matrix. Clasts are subangular to angular and are poorly sorted. Most clasts are granitic and are derived from the Wilson Ridge pluton.

Quaternary conglomerates and clastic units of the Muddy Creek Formation are dissected by recent channels and channel deposits. Recent deposits are poorly indurated to non-indurated gravelly conglomerates and coarse sands.

**Interpretation of Clastic Sedimentary Rocks**

Conglomerates of the Muddy Creek Formation dip gently ($\leq 20^\circ$) to the west on the western flank, and to the east on the eastern flank of Wilson Ridge and represent a proximal alluvial fan depositional sequence. Dip is interpreted as a primary dip, although moderate stratal rotation in response to regional high-angle faulting cannot be ruled out. Growth faults and reverse-drag flexing in correlative units of the Muddy Creek Formation have been described by Scott (1988) east of the River Mountains and near Malpais Flat Top Mesa. Growth faults were not observed in the Muddy Creek Formation exposed in the thesis area. Angularity of clasts and poor sorting suggests a short transport distance. Heterogeneity of clasts within different beds and along strike within individual beds records a local provenance. These sediments were deposited in grabens adjacent to local highs (e.g., the Wilson Ridge horst) that formed during late-Miocene high-angle faulting. Sandstones possibly represent distal alluvial fan/alluvial plain braided stream deposits.
In this study, "mafic enclave" is used as a non-genetic term that refers to any grey to dark black, isolated rock entirely incorporated in a granitoid host rock (Didier, 1973).

"Inclusion" is a term that has several connotations. "Inclusion" is frequently used to describe any distinct dark patch within granitoids, including cumulate material, restite material, other cognate wall rock, and mafic magmas injected into, or incorporated at a boundary layer within granitoids and volcanic rocks (Didier, 1973; Eichelberger, 1975). In this study I use the term "inclusion" synonymously with enclave. "Inclusion" is purely descriptive and nongenetic. "Mafic blob" is a term frequently used to describe enclaves that show clear evidence of liquid-liquid magma commingling. In this thesis, "mafic blob" is restricted to this definition. "Xenolith" is reserved for mafic enclaves that represent already solidified wall rock and genetically unrelated country rock that was stoped from the roof or sidewalls of the pluton and incorporated in the magma.

The term "mixing" is frequently used "to include all scales and types of interactions between coexisting magmas" (Weibe, 1980). In this study, "mixing" is restricted to thorough and complete interaction between contrasting magmas to produce hybrid magmas of intermediate composition in which the identities of the parental magmas are obscured.
The terms "mixing" and "commingling" are not synonymous. "Commingling" is reserved for rocks that show evidence of interaction between contrasting magmas, but the interaction is incomplete and evidence for the parental (end member) magmas is preserved. "Assimilation" will be used synonymously with "commingling" in this study. Both terms describe a process that involves both mechanical disintegration and chemical reaction and re-equilibration between a magma and any given contaminant (Hyndman, 1985).

THE WILSON RIDGE PLUTON

Introduction

The Wilson Ridge pluton is composed of two plutonic suites, each of which may have formed by several intrusive pulses. The main volume of the pluton is comprised of quartz monzonite, quartz monzodiorite, and monzodiorite, and is herein referred to as the Teakettle Pass suite. Contacts between these three phases are gradational, indicating that these rocks are comagmatic. A smaller mafic pluton consisting of coarse-grained diorite and pegmatitic diorite crops out on the western slope of Wilson Ridge, and is herein referred to as the Horsethief Canyon diorite. The Horsethief Canyon diorite is dated at 13.3 ±0.4 Ma (Table 1) (date provided by Paul Damon, University of Arizona) and the quartz monzonite of the Teakettle Pass suite is dated at 13.6 ±0.6 Ma (Anderson et al., 1972). Both ages are K-Ar biotite dates.
Table 1. New K–Ar Date for the Wilson Ridge Pluton

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<tr>
<th>Sample</th>
<th>K%</th>
<th>Radiogenic Ar pm/g</th>
<th>% Ar atmospheric</th>
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<tr>
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<td>7.092</td>
<td>164.3</td>
<td>15.1</td>
<td>13.3+/−0.4</td>
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</table>


Field Relationships

Horsethief Canyon diorite crops out near the southwestern margin of the pluton and has an outcrop area of approximately 4 km² (Figure 3). Rocks of the Teakettle Pass suite intrude Horsethief Canyon diorite and crop out over an area of 80 km² in the northern and central parts of the pluton. Exposed in an outcrop area of 60 km², quartz monzonite is the dominant phase of the Teakettle Pass suite. Contacts between monzodiorite-quartz monzodiorite and quartz monzonite dip moderately (20°) north and are gradational. In Horsethief Canyon the contact zone is 50 to 100 m wide. Changes in mineralogy from monzodiorite to quartz monzonite include an increase in quartz and orthoclase and a decrease in biotite, hornblende, and sphene. Monzodiorite and quartz monzodiorite locally display a moderately strong fabric that is defined by the parallel alignment of biotite, prismatic hornblende, and laths of plagioclase. Foliation in monzodiorite is variable. Quartz monzonite is unfoliated. Horsethief Canyon diorite is unfoliated and is locally cut by mafic pegmatite veins and vugs composed of spectacular prismatic hornblende (up to 10 cm in length). Diorite is intruded by, and incorporated as angular xenoliths in intermediate phases of the Teakettle Pass suite. Diorite is also net-veined by fine-grained leucocratic quartz monzonite. This field evidence indicates that the diorite was completely solidified prior to the intrusion of the Teakettle Pass suite.

Intermediate rocks of the Teakettle Pass suite contain mafic enclaves that locally comprise more than 75 percent by volume of the rock. Enclaves are also present in quartz monzonite, but to a lesser degree than in the intermediate
phases of the suite. Two types of mafic enclaves occur in the Teakettle Pass suite. These are:

1. **Basalt enclaves** are lensoidal, fusiformal, tabular and pillow-shaped. Basalt enclaves commonly have crenulate margins, fine grained borders, and are locally boudinaged (Figure 7). Many enclaves show a weak internal foliation that is coplanar with the foliation in the host as well as with the mesoscopic foliation defined by the alignment of the enclaves themselves. Enclaves are typically 20 to 50 cm long and are rarely isolated; more typically they cluster in inclusion-rich tabular zones that display strong flow foliation near their margins (Figure 8). Inclusion zones occur throughout the pluton in the intermediate phases of the Teakettle Pass suite. In two dimensions, inclusion zones range from less than 1 m (width) by only 5 m (length), to 10 m (width) by 500 m (length). There is a continuum in shape from enclaves that are bulbous and ellipsoidal to those that are thin, tabular mafic selvages and schlieren, and ultimately to the mafic component in foliated quartz monzodiorite and monzodiorite (Figure 9).

2. **Medium-to coarse-grained diorite enclaves** are mineralogically equivalent to Horsethief Canyon diorite. Diorite enclaves range in size from 5 cm to over 2 m, although the average size is 40 cm (long dimension). Diorite enclaves are typically angular, blocky, and are commonly veined by fine to medium grained leucocratic quartz monzonite to monzodiorite (Figure 10). Foliation in host rocks and lensoidal basaltic enclaves is deflected around large diorite enclaves.
FIGURE 7.

a. Photograph shows lensoidal and tabular basaltic enclaves that locally grade into mafic schlieren. Mesoscopic foliation is coplanar with microscopic foliation in both the host and the enclaves. Hammer is 40 cm long.

b. Boudinaged and lensoidal enclaves and mafic pillows in felsic host. Note contact between enclave-rich zone (above hammer) and wispy mafic enclaves (below). This contact may represent the margin of a mechanically disrupted mafic dike.
FIGURE 8. Photograph shows a tabular zone of basaltic enclaves in a monzodiorite host. These tabular zones are interpreted as synplutonic basalt dikes that intruded a felsic host and were subsequently mechanically disrupted by magmatic flow. Scale bar is 1 meter.
FIGURE 9. Photographs displaying progressive mechanical disruption of mafic enclaves. Scale bar is 3.0 cm.

a. Aligned lensoidal mafic enclaves in mozodiorite host. Lenses are sheared remnants of mafic dikes. Shearing occurred during magmatic flow.

b. Continued shearing reduces enclaves into mafic schlieren and selvages. Mineral and matrix components of enclaves are incorporated in felsic host by mechanical disruption.

c. Final stage of mechanical breakdown produces a foliated monzodiorite. Enclaves are nearly completely disrupted and incorporated in host.
FIGURE 10. Photograph shows dark, angular and blocky diorite enclaves in quartz monzonite host. Diorite enclaves are commonly net veined by fine-grained leucocratic quartz monzonite to monzodiorite. Diorite was completely solidified prior to incorporation in the felsic host. Rock hammer is 38 cm long.
**Petrography**

**Teakettle Pass Suite**

Quartz monzonite, the dominant phase of the Teakettle Pass suite, is coarse grained, hypidiomorphic granular, and leucocratic. Major minerals are quartz, plagioclase, orthoclase, and biotite (Table 2). Quartz (19%) forms anhedral to subhedral equant crystals. Orthoclase (25%) is anhedral to subhedral and commonly shows micrographic texture with rod-like blebs of intergrown quartz. Plagioclase (41%) forms subhedral to euhedral lath-shaped crystals that display oscillatory zoning as well as simple and polysynthetic twinning. Small plagioclase crystals are incorporated in subhedral orthoclase crystals (synneusis texture). Biotite typically forms subhedral to euhedral hexagonal plates (10%). Quartz monzonite contains only minor (<5%) subhedral prismatic hornblende, honey-yellow subhedral sphene (<1%), acicular apatite (<1%), and trace amounts of zircon.

Quartz monzodiorite and monzodiorite are medium grained, hypidiomorphic granular, and mesocratic. Polysynthetically (010) twinned plagioclase with oscillatory zoning is the dominant mineral (45%). Quartz and orthoclase crystallized late and form small (<1mm) anhedral interstitial crystals (<20%). Mafic minerals include subequal amounts of pleochroic subhedral to euhedral biotite and hornblende (total hornblende + biotite = 40%). Hornblende commonly displays simple (100) twinning. Accessory minerals include subhedral to euhedral (0.5-2.0 mm) sphene (1%-2.5%), apatite (0.5%-2%), and trace amounts of zircon. Even though evidence of strain is rare, quartz crystals in
Table 2. Summary of Petrography for the Wilson Ridge Pluton and River Mountains Basalt

<table>
<thead>
<tr>
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<th>Monzonite (2)</th>
<th>Monzodiorite (5)</th>
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<td>Biotite</td>
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<td>Sphene</td>
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<td>Apatite</td>
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</tr>
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<td>Matrix</td>
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Number in parentheses is the number of samples averaged for rock mode.

Mineral modes were determined by thin section point counts (500/rock).
monzodiorite and quartz monzodiorite show undulatory extinction and rare sub-grain development. Recrystallization of quartz is uncommon in quartz monzodiorite and monzodiorite. Quartz monzodiorite and monzodiorite locally display a strong mesoscopic foliation defined by the parallel alignment of plagioclase laths, hornblende prisms, and biotite (Figure 11).

**Horsethief Canyon Diorite**

Horsethief Canyon diorite is medium to coarse grained, hypidiomorphic granular, and mesocratic to melanocratic. Diorite is composed of subhedral to euhedral prismatic (1-4 mm) hornblende crystals (35%). Hornblende shows green, yellow and brown pleochroism and commonly displays simple (100) twinning. Biotite crystals are subhedral to euhedral (15%) and polysynthetically twinned plagioclase form subhedral oscillatory zoned lath-shaped crystals (50%). Anhedral interstitial quartz and orthoclase are present in minor amounts (<10%). Megascopic (1-2mm) honey-yellow sphene is the dominant accessory phase (2%-4%). Apatite (1-2%) occurs as small (<0.5mm) rod-like euhedra.

**Enclaves**

Basalt enclaves are fine grained to porphyritic and contain plagioclase phenocrysts (<5%) 1 to 3 mm in size. Groundmass is composed of subparallel, lath-shaped, subhedral plagioclase microlites (50%), anhedral to subhedral pleochroic hornblende (10%), and biotite (30%). Accessory minerals include anhedral to subhedral sphene (<1%), acicular apatite euhedra (3%), and magnetite (3%). Basalt enclaves lack the clinopyroxene and olivine phenocrysts observed in dikes of the Wilson Ridge pluton and lava flows of the River
FIGURE 11. Photomicrograph shows foliation in monzodiorite. Quartz monzodiorite and monzodiorite commonly display a strong mesoscopic foliation defined by the subparallel alignment of plagioclase, hornblende, and biotite. Foliation is produced by magmatic flow and evidence for strain is rare. Note subparallel alignment of polysynthetic and simple twins in plagioclase crystals (P). Foliation is parallel to arrow on the left side of the figure. Scale bar is 2 mm. Other minerals include biotite (B), hornblende (H), and quartz (Q).
Mountains (Smith, 1983). The presence of biotite and hornblende in enclaves is attributed to re-equilibration of the enclaves during the cooling of the host. The influx of mobile elements and volatiles from the felsic host into the enclaves may have promoted the growth of hornblende and biotite at the expense of primary phases. Similar mineralogy is observed in basalt enclaves in Sierra Nevadan plutons (Reid et al., 1983) and may be attributed to static diffusion processes in mixed magmas (Yoder, 1973; Kouchi and Sunagawa, 1982; Watson, 1983).

**Sphene**

Sphene is a ubiquitous phase in both the Teakettle Pass suite and the Horsethief Canyon diorite. It varies in concentration from 0.5 to 4% and occurs as large (1-2 mm) subhedral to euhedral rhombic crystals. Sphene phenocrysts are rarely interstitial and are commonly intergrown with quartz and orthoclase (Figure 12). Sphene crystallized late, but is clearly a liquidus phase.

**GEOCHEMISTRY**

**Instrumental techniques**

Twenty-eight samples of the Wilson Ridge pluton were analyzed for major and trace elements. Analyses of basalt from the northern River Mountains are from Smith et al. (1989) (Table 3). Whole-rock major-element chemistry was determined by Inductively Coupled Plasma (ICP) techniques at Chemex Labs, Inc., Sparks, Nevada. Rare-earth elements (REE) and Co, Ta, Hf, Th, V, Sr, Rb, Ba, and Sc, were analyzed by Instrumental Neutron Activation Analysis (INAA) at the Phoenix Memorial Laboratory, University of Michigan. The multi-element
FIGURE 12.

a. Photomicrograph (cross polars) of monzodiorite showing euhedral sphene (S) and anhedral intergrown quartz (Q). Scale bars are 0.5 mm.

b. Photomicrograph (plane polarized light) showing numerous euhedral rhombic sphene in diorite. Other minerals include plagioclase (P), hornblende (H), biotite (B), and magnetite (M).
Table 3. Representative Chemical Data for the Wilson Ridge Pluton

<table>
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<tr>
<th>Sample NO.</th>
<th>Teakettle Pass Suite</th>
<th>Quartz Monzonite</th>
<th>Quartz Monzodiorite</th>
<th>Monzodiorite</th>
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standards G-2, BHVO-1, RGM-1, and GSP-1 were used as internal standards. Average percentage error values for REE and trace elements analyses are presented in Table 4.

**Major Elements**

Intermediate rocks of the Teakettle Pass suite and Horsethief Canyon diorite vary continuously between 52 and 70 weight percent SiO₂ (Figure 13) and are calc-alkaline (Figure 14). TiO₂, Al₂O₃, Fe₂O₃, MgO, and CaO decrease linearly with increasing SiO₂. P₂O₅ and MnO also decrease but show considerable scatter. Na₂O and K₂O increase directly with increasing SiO₂, but data are scattered. Basalt sample (218) from the River Mountains is similar in major element chemistry to mafic dikes and inclusions of the Wilson Ridge pluton, and on Harker diagrams plots near the end of the variation trend for each element. These trends may represent mixing lines between basaltic and felsic end members. High Al₂O₃ content in one inclusion (sample 66) is attributed to element influx from the host that resulted in crystallization of biotite and hornblende in the inclusion.

At many localities in the Lake Mead area, volcanic and plutonic rocks were strongly metasomatized (Feuerbach, 1986; Smith et al., 1989). Metasomatism resulted in either potassium or sodium enrichment. Potassium enrichment is accompanied by sodium depletion, and vice versa. Metasomatized rocks of the Wilson Ridge pluton show no obvious lithological or petrographic evidence of alteration or recrystallization, therefore the extent of metasomatism was evaluated by geochemical techniques. Metasomatized rocks were identified by use of a
Table 4. Percent Error for Trace and Rare-Earth Element Analyses

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FIGURE 13. Harker variation diagrams for the Wilson Ridge pluton and basalt of the River Mountains.
Na$_2$O vs. K$_2$O plot (Figure 15) with the range of unaltered intermediate and felsic rocks outlined (Carmichael et al., 1974). Rocks that fall within the field of unaltered rocks were considered to be unmetasomatized. Eighty percent of Wilson Ridge samples plot in the field of unaltered rocks. Alaskite, granite pegmatite, and aplite dikes were especially affected by K metasomatism and display either high K or Na contents. For example dike (46) is enriched in K$_2$O (9.4%) and dike (68) is high in Na$_2$O (8.88%).

**Trace Elements**

The range in rare-earth element (REE) concentrations in rocks of the Wilson Ridge pluton is shown in Figure 16. All samples of the Teakettle Pass suite and the Horsethief Canyon diorite show light REE enrichment, lack Eu anomalies and convex down REE patterns. REE content increases with decreasing SiO$_2$ and chondrite normalized REE patterns roughly "stack" with enclaves, dikes and basalt flows having the highest REE concentrations and felsic dikes the lowest. The inverse relationship between REE content and SiO$_2$ and the "stacking" of curves for intermediate rock types are compatible with the mixing of mafic and felsic end members but not with large-scale fractionation of either plagioclase or hornblende.

The transition elements Sc, Co and Ti decrease with increasing SiO$_2$ (Figure 17). These variations may result from small amounts of hornblende, biotite, clinopyroxene, or magnetite fractionation. The high field strength elements Hf and Ta and the lithophile elements Ba and Rb show considerable scatter. Sr decreases with increasing SiO$_2$. The lithophile elements are mobile
FIGURE 15. $K_2O$ vs. $Na_2O$ diagram showing the field of "unaltered" intermediate and felsic plutonic rocks (from Carmichael et al., 1974). Filled triangles are rocks of the Teakettle Pass suite, open triangles are felsic and intermediate dikes.
FIGURE 16. Chondrite normalized rare-earth element (REE) distributions for the Wilson Ridge pluton. Note the inverse relationship between silica content and REE abundance and lack of negative Eu anomalies.
FIGURE 17. Trace element variation diagrams for the Wilson Ridge pluton and basalt from the River Mountains.
during metasomatism, therefore scatter in these elements is attributed to post-emplacement alteration.

With respect to trace elements, basalt enclaves of the Wilson Ridge pluton are similar to basalt dikes and to basalt flows of the northern River Mountains (Figure 18). This correlation and abundant field data imply that the basalt enclaves in the Wilson Ridge pluton were injected as high temperature magmas; they do not represent restite, cumulate phases, or exotic wall rock. However, one enclave (58) (Table 3) differs by having lower total REE abundances. Whether this sample represents a separate magma, a hybridized magma, or restite is unknown.

DIFFERENTIATION MODELS

Introduction

Field and petrographic evidence described above suggests that the commingling of felsic and mafic magmas was an important process in generating intermediate rocks of the Wilson Ridge pluton. I evaluated the importance of magma commingling by employing open-system (AFC) models using both Rayleigh fractionation and commingling.

Major element models were generated by the program XLFRAC (Stormer and Nicholls, 1978). XLFRAC solves a series of least squares mass balance equations to determine the proportions of added or subtracted phases required to produce a fractionated rock from a given parent. Open-system (AFC) models were generated using the DePaolo equation (DePaolo, 1981) to model
FIGURE 18. Chondrite normalized spider diagram comparing basalt from the River Mountains, and a mafic dike and an enclave from the Wilson Ridge pluton.
simultaneous assimilation and fractional crystallization (AFC). Distribution coefficients are average values reported in Arth (1976) (Table 5). Mineral compositions are from Deer et al. (1972) and Thompson (1985) (Table 6).

**End Members For AFC Models**

Major and trace element open-system models were developed using Powerline Road basalt from the northern River Mountains (218) and quartz monzonite from the Wilson Ridge pluton (42) as end member compositions. River Mountains basalt was chosen because it lacks obvious mesoscopic or microscopic mixing textures and is chemically similar to basalt enclaves and synplutonic mafic dikes that cut the Wilson Ridge pluton. Homogeneous quartz monzonite of the Teakettle Pass suite also lacks abundant mixing textures and is the most voluminous felsic phase of the pluton. More silicic rocks (>70% SiO$_2$) of the Wilson Ridge pluton are unlikely end-members since they are fractionated and volumetrically minor.

**Modal Apatite and Sphene**

The presence of modal sphene and apatite does not appreciably effect major element abundances, however they control rare earth element concentrations in many granites (Fourcade and Allegre, 1981; Gromet and Silver, 1983; Noyles et al. 1983) and thus, modal sphene and apatite must be considered in all REE and trace element models. The wide variation in abundances of accessory phases between samples results in data scatter on plots using rare earth and other trace elements and makes rigorous modeling using these elements difficult.
Table 5. Distribution Coefficients Used in Trace Element Models

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<td>Sm</td>
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<td>0.05</td>
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<td>Yb</td>
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<td>Cr</td>
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<td>10</td>
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<tr>
<td>V</td>
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<td>45</td>
<td>--</td>
<td>50</td>
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<tr>
<td>Co</td>
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<td>1.2</td>
<td>10</td>
<td>9</td>
<td>20</td>
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<tr>
<td>Th</td>
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<td>0.007</td>
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</table>

Note: Numbers are average mineral/liquid distribution coefficients from Arth (1976) and Honjo and Leeman (1987).
Table 6. Mineral Compositions Used in Major Element Models

Oxides in weight percent

<table>
<thead>
<tr>
<th></th>
<th>Hornblende(1)</th>
<th>Biotite(2)</th>
<th>Biotite(1)</th>
<th>Andesite(2)</th>
<th>Labradorite(2)</th>
<th>Orthoclase(2)</th>
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<tr>
<td>$\text{SiO}_2$</td>
<td>43.50</td>
<td>39.14</td>
<td>36.14</td>
<td>58.10</td>
<td>52.96</td>
<td>64.46</td>
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<td>$\text{Al}_2\text{O}_3$</td>
<td>11.29</td>
<td>13.10</td>
<td>12.88</td>
<td>26.44</td>
<td>29.72</td>
<td>18.55</td>
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<tr>
<td>$\text{Fe}_2\text{O}_3$</td>
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<td>17.99</td>
<td>16.38</td>
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<td>0.14</td>
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<tr>
<td>$\text{CaO}$</td>
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<td>1.64</td>
<td>0.00</td>
<td>7.84</td>
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<td>12.65</td>
<td>13.77</td>
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<td>0.00</td>
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<td>$\text{Na}_2\text{O}$</td>
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<td>0.98</td>
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<td>$\text{K}_2\text{O}$</td>
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<td>$\text{TiO}_2$</td>
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<table>
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<tr>
<th></th>
<th>Quartz(2)</th>
<th>Clinopyroxene(1)</th>
<th>Olivine(1)</th>
<th>Magnetite (2)</th>
<th>Ti Magnetite (2)</th>
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<tr>
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<td>0.02</td>
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<td>$\text{Fe}_2\text{O}_3$</td>
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<td>7.75</td>
<td>22.12</td>
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<td>$\text{MgO}$</td>
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<td>1.97</td>
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<td>0.35</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$\text{K}_2\text{O}$</td>
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<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$\text{TiO}_2$</td>
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<td>0.63</td>
<td>0.00</td>
<td>0.00</td>
<td>18.70</td>
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(1) Mineral analyses from volcanic rocks of the Hamblin-Cleopatra volcano (Thompson, 1985)
(2) Mineral analyses from Deer et al. (1972)
Major Element Models

I tested several possible evolutionary paths for intrusive phases of the Wilson Ridge pluton using the program XLFRAC. Only combined fractional crystallization and mixing (AFC) models were successful in generating the intermediate rocks of the Teakettle Pass suite and Horsethief Canyon diorite.

The Horsethief Canyon diorite may have been produced by the fractionation of 16.5% clinopyroxene and 1% magnetite from basalt (218) and the addition of 28% liquid with the composition of Teakettle Pass suite quartz monzonite (42). R, the ratio of amount assimilated/amount fractionated is 1.6 for this model (Table 7). In predominately mafic mixtures such as predicted by this model, homogenization of the mixed magma will occur when the equilibrium temperature is above the solidus of basalt (Koyaguchi, 1986). The resulting rock will show few mixing textures. Thus, the scarcity of mixing textures observed in both field and petrographic studies of the Horsethief Canyon diorite may be attributed to a large mafic to felsic ratio of mixed phases.

Modeling of the intermediate rocks of the Teakettle Pass suite also requires both crystal fractionation and magma mixing. Monzodiorite may have formed by fractionation of 2.75% magnetite and 24% clinopyroxene from basalt (218) and the addition of 34% liquid with the bulk composition of Teakettle Pass suite quartz monzonite (42) (R=1.27)(Table 3 and Table 5). Quartz monzodiorite may have been formed by fractionation of 1.7% magnetite and 4.7% biotite from monzodiorite and addition of 34% quartz monzonite (Table 3 and Table 5) (R=5.31). Fractionation of clinopyroxene, biotite, and magnetite is
Table 7. Major Element Fractional Crystallization Models

<table>
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<th>Model</th>
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<td>Phase</td>
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<tr>
<td>Clinopyroxene</td>
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<td>--</td>
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<tr>
<td>Fe–Ti oxide</td>
<td>-1.3</td>
<td>-2.8</td>
<td>-1.7</td>
</tr>
<tr>
<td>biotite</td>
<td>--</td>
<td>--</td>
<td>-4.7</td>
</tr>
<tr>
<td>42 (Quartz Monzonite)</td>
<td>+28.5</td>
<td>+34.9</td>
<td>+33.9</td>
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Residuals

<table>
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<tr>
<td>SiO2</td>
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<td>0.04</td>
</tr>
<tr>
<td>Al2O3</td>
<td>-0.23</td>
<td>-0.36</td>
<td>-0.04</td>
</tr>
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<td>Fe2O3</td>
<td>-0.23</td>
<td>-0.23</td>
<td>0.02</td>
</tr>
<tr>
<td>CaO</td>
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<td>-0.93</td>
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<td>0.86</td>
<td>0.2</td>
</tr>
<tr>
<td>Na2O</td>
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<td>0.21</td>
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<tr>
<td>K2O</td>
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<td>-0.28</td>
</tr>
<tr>
<td>TiO2</td>
<td>0.04</td>
<td>-0.44</td>
<td>-0.03</td>
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</table>

Total % subtracted

17.8  26.6  6.4

Total % added

28.5  34.9  33.9

Sum of squares of the Residuals

2.07  3.08  0.18

Description of Models:
1. Parent 218, Daughter 41 (Diorite)
2. Parent 218, Daughter 59 (Monzodiorite)
3. Parent 43 (Monzodiorite), Daughter 44 (Quartz Monzodiorite)
supported by mineral modes. The large mafic to felsic magma ratio required in this mixing model agrees well with field data. Mafic to felsic component ratios vary from 0.40 to 0.75 in intermediate rocks of the Teakettle Pass suite.

**Trace Element Models**

We refined major element AFC models by modeling the REE, Sc, Ti, Co, Hf, Ta, and Th. In most models R values and fractionated phases agree closely with major element models (Table 8). Horsethief Canyon diorite may have been produced by fractionation of 12% clinopyroxene, 1.4% magnetite, and 1% apatite from basalt (218) and addition of 5% liquid with the composition of quartz monzonite (42) (R=0.40) (Figure 19c).

Quartz monzodiorite and monzodiorite of the Teakettle Pass suite may have been formed by fractionation of 9.4% clinopyroxene, 1.7% magnetite, and 0.9% apatite from basalt (218) and the addition of 15% liquid of the composition of quartz monzonite (42) (R=.50) (Figure 19b).

Trace element models indicate smaller amounts of fractionation and higher mafic to felsic mixing ratios than major element models. Trace element modeling also suggests that apatite was fractionated from basalt (218). Small amounts of apatite removal are reasonable in light of the occurrence of up to 1.5% apatite in sample 218. Apatite is also a common phase in many of the enclaves.
Table 8. Trace-Element Models

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<td>Model</td>
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<td>Th</td>
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</tr>
<tr>
<td>La</td>
<td>111.3</td>
<td>81.3</td>
</tr>
<tr>
<td>Ce</td>
<td>171.8</td>
<td>167</td>
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<tr>
<td>Nd</td>
<td>91.8</td>
<td>83.5</td>
</tr>
<tr>
<td>Sm</td>
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<td>10.9</td>
</tr>
<tr>
<td>Eu</td>
<td>2.38</td>
<td>1.9</td>
</tr>
<tr>
<td>Yb</td>
<td>2.75</td>
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</tr>
<tr>
<td>Lu</td>
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<td>0.3</td>
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<tr>
<td>Ta</td>
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<td>1.6</td>
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<tr>
<td>Hf</td>
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<td>8.7</td>
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<tr>
<td>Sc</td>
<td>22.8</td>
<td>9.8</td>
</tr>
<tr>
<td>Ti (wt %)</td>
<td>1.03</td>
<td>0.97</td>
</tr>
<tr>
<td>Co</td>
<td>22.2</td>
<td>11.3</td>
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Concentrations in ppm, except Ti (in wt %)

Model 1=Basalt (218)-9.4% cpx, 1.7% magnetite, 0.9 % apatite + 9.6% quartz monzonite (42) to produce quartz monzodiorite (59) or monzodiorite (56)

Model 2=Basalt (218)-11.5% cpx, 1.4% magnetite, 1.1 % apatite + 4.9 % quartz monzodiorite (42) to produce diorite (41)
FIGURE 19. Chondrite normalized spider diagrams comparing model rocks produced by assimilation and fractional crystallization (AFC) processes.

a. End-members for mixing models.

b. Model for generation of intermediate rocks (model 1, table 6).

c. Model for generation of diorite (model 2, table 6).
ORIGIN OF ENCLAVES

Introduction

The great diversity in size, shape, texture, and composition of mafic enclaves precludes a single explanation for their occurrence in granitoid rocks. The origin of each enclave must be critically evaluated on an individual basis. The variation of contact relationships between inclusions and host rocks and variation in internal texture suggests that there are many probable origins for enclaves. These include:

1) auto[liths] - cognate inclusions which are genetically related to the host and represent earlier formed, sidewall crystallized cumulate phases that were subsequently incorporated in the felsic host (Bateman, 1963; Didier, 1973; Sawka, 1988).

2) xenoliths - inclusions formed by magmatic stoping of genetically unrelated country rock (Bateman et al., 1963; Cobbing and Pitcher, 1972).

3) restite - inclusions which represent the refractory residuum from partial melting (Moore, 1963; Presnall and Bateman, 1973; White and Chappell, 1977).

4) dikes - inclusions which represent high-temperature synplutonic mafic magmas injected (or incorporated at a boundary layer) into a liquid or semi-liquid felsic host (Eichelberger, 1975; McBirney, 1980; Taylor et al., 1980; Reid et al., 1983; Bacon, 1986; Barnes et al., 1986; Hyndman and Foster, 1988; Hill, 1988).
There are commonly several different inclusion types within a given pluton. Individual inclusions show textures and have chemical characteristics that suggest a complex history of evolution for the inclusion prior to incorporation in the host (Didier, 1973; Barbarin, 1987).

The degree to which inclusions contribute to the hybridization of any igneous system is controlled by three factors:

1) **bulk compositional differences** between the commingling phases \( \delta C \) (Bacon 1986; Furman and Spera, 1985). A large compositional difference between two magmas will inhibit commingling and assimilation.

2) **thermal difference** between the two phases involved \( \delta T \) (Furman and Spera, 1985; Mcbirney, 1980, Reid et al., 1983) The smaller the \( \delta T \), the greater the opportunity for hybridization.

3) **extent of mechanical disruption** of the inclusions and the physical redistribution of their components by magmatic flow (Hyndman and Foster, 1988; Hill, 1988). A vigorously convecting magma chamber would be conducive to mechanical mixing of magmas and enclaves.

**Origin of Basalt Enclaves of the Teakettle Pass Suite**

Chilled borders, crenulate margins, boudinage, and pillow-like geometries of basalt enclaves of the Teakettle Pass suite strongly suggest that they were liquid or semi-liquid at the time of their incorporation in the felsic host (Didier, 1973; Taylor et al., 1980; Barbarin, 1987). The abundance of lensoidal and phacoidal inclusions, and the lack of strain within the inclusions and most phases of the Teakettle Pass suite indicates that enclaves were deformed while still partially
molten. Similar liquid-liquid mixing textures have been described at other mafic enclave localities (Pabst, 1928; Larsen, 1948; Reid et al., 1983; Vernon, 1983; Furman and Spera, 1985; Bacon, 1986; Hyndman and Foster, 1988; Hill, 1988).

Chemical similarities between enclaves and dikes of the Wilson Ridge pluton, and lavas of the northern River Mountains indicates that basalt enclaves represent chilled blobs of magma; not cumulate material or restite. Tabular zones of mafic enclaves are interpreted as synplutonic basalt dikes that intruded a crystal-liquid quartz monzonite host. Shear during magmatic flow contributed to the deformation and mechanical breakdown of synplutonic mafic dikes. Most basalt enclaves were physically disrupted and mechanically redistributed by magmatic flow within a dynamic magma chamber. Once incorporated in the felsic host, blobs of basaltic magma deformed plastically into ellipsoids and lenses. Enclaves became entrained in the convecting magma chamber and were further reduced in size by flow shear (Figure 20). Enclaves now manifest themselves as tabular inclusion swarms. A similar origin for tabular and pillowed synplutonic mafic dikes has been described in the Idaho Batholith by Hyndman and Foster (1988) and in the San Jacinto Intrusive Complex by Hill (1988).

**Origin of Diorite Enclaves**

The angular, blocky, and fractured nature of the diorite enclaves and sharp contacts with host rocks suggest that they were completely solid at the time of their incorporation. Diorite enclaves are interpreted as xenoliths. As quartz monzonite of the Teakettle Pass suite was emplaced, rapid exsolution of volatiles may have resulted in net veining and stoping of Horsethief Canyon diorite.
FIGURE 20. Simplified model for the development of the Wilson Ridge pluton. Large volumes of mafic magma were injected into a quartz monzonite host. Shear produced by magmatic flow contributed to the deformation and mechanical breakdown of mafic enclaves. Basalt enclaves were physically disrupted and mechanically redistributed by magmatic flow within a dynamic magma chamber. Horsethief Canyon diorite pluton formed earlier and was completely solidified at the time of the emplacement of Teakettle Pass quartz monzonite. Cogenetic volcanic rocks were detached by faulting at about 13.4 Ma. Volcanic rocks are now exposed 20 km to the west in the River Mountains.
In situ hydrofracting of diorite wall rock facilitated assimilation and incorporation of diorite xenoliths within the felsic magma.

MODELS FOR MODES OF PLUTON EMBEDMENT

Introduction

Emplacement models for the Wilson Ridge pluton are difficult to construct because contacts between the pluton and country rocks are poorly exposed or are high-angle normal faults. The southern contact between foliated and lineated rocks of the Teakettle Pass suite and the Precambrian basement is the only exposed contact between the pluton and country rock. This contact dips to the southwest (20-30°) and is roughly coplanar with the predominant regional metamorphic foliation (Figure 6). Reconnaissance field mapping suggests that foliation in the Precambrian basement immediately south of the Wilson Ridge pluton is relatively consistent, indicating a minimal amount of emplacement-related deformation.

The original shape of the pluton is difficult to constrain because only one contact between the pluton and country rocks is exposed and because of faulting and erosion. However, the present outcrop pattern of the Teakettle Pass suite may represent the cross section of the pluton (because of a gentle northward tilt). The plan-view of the outcrop pattern appears to be crudely elliptical.

Depth of Magma Generation

Quartz monzonite of the Teakettle Pass suite may have formed by partial melting of mid-crustal granulite (Mills, 1985). Silicic melts were probably formed
by ponding of hot, mantle derived basalt at mid-crustal levels (Hildreth 1981).

**Depth of Emplacement**

Detailed field mapping by Naumann (1987) in the northern Wilson Ridge pluton/Boulder Wash volcanics and Smith (1983) in the River Mountains revealed that the Wilson Ridge pluton intruded its volcanic cover, suggesting that it is an epizonal pluton. The deepest structural level of the pluton is exposed near the southern margin. Assuming less than 5 degrees of northward tilting, the deepest part of the pluton was emplaced at depths of less than ≈2.5 km.

**Diapiric Emplacement**

Magma bodies assume a diapiric shape because this is a low energy configuration (Ramberg, 1981). Diapirs ascend due to density contrasts between the ascending diapir and the surrounding rocks, and are emplaced at a level of neutral buoyancy. Diapiric emplacement is generally associated with deep (≥ 7 km) crustal levels, requires structural disruption of the country rocks, and generally results in high-angle contacts between the pluton and the country rocks (Hyndman, 1985; Pitcher et al., 1985).

**Passive Emplacement**

Many shallow-level intrusions result from passive emplacement (Hyndman, 1985). This style of emplacement is characterized by a combination of cauldron subsidence, cauldron upheaveal, doming, and stoping. Magma may ascend along crustal fractures and anisotropies in a piston-like manner (Pitcher, 1979). These shallow-level intrusions are commonly associated with caldera formation, large scale ring fractures and dikes, and production of pyroclastic rocks.
It is important to distinguish between the geometry of a rising pluton and the shape of the emplaced pluton. Leake (1978) suggested that many granitic bodies travel upward through the crust with a shape completely different than their final shape. At deeper crustal levels a magma body may ascend diapirically, but at shallow crustal levels magma may ascend passively. As magma reaches shallow levels, it may spread out laterally and gently dome the roof rocks (Pitcher, 1979).

Discussion

A forceful mode of emplacement for the Wilson Ridge pluton can be ruled out because:

1. Foliation in Precambrian metamorphic rocks was not appreciably disrupted by emplacement of the Wilson Ridge pluton.

2. The contact between the pluton and the country rock is low-angle.

Evidence for passive emplacement is minimal. Pyroclastic rocks are associated with a caldera at Hoover Dam (Mills, 1985). Pre-extension reconstructions place this volcanic section above the Wilson Ridge pluton (Weber and Smith, 1987). In addition, slight doming of the roof overlying the Wilson Ridge pluton cannot be ruled out because of the concordant foliation in the pluton and country rock. Even though evidence is minimal, near-surface passive emplacement during active extension is the most reasonable model for emplacement of the Wilson Ridge pluton.
Depth of Magma Commingling

Field and geochemical data suggest that mixing occurred prior to ascent, during ascent and following emplacement of the Wilson Ridge pluton. This model suggests that there is not a single depth of commingling, but rather that the interaction between the two contrasting magmas is ongoing both vertically in the crust and with time. This model may explain the variation in shape and degree of mechanical breakdown of enclaves within the Teakettle Pass suite. Rather than requiring all enclaves to be physically disrupted and mechanically reduced in size by convection within the magma chamber, which is implied for strictly post-emplacement magma commingling, magmatic flow during ascent may have also contributed to mechanical mixing and hybridization. Those enclaves that show the greatest amount of mechanical breakdown may have been injected into the felsic magma prior to ascent of the Wilson Ridge pluton. Mechanical disruption therefore occurred prior to and during ascent. In addition, the degree of plastic deformation and mechanical breakdown of some enclaves may be attributed to the "state" (i.e., the degree of crystallinity, viscosity, and temperature) of both the injected magma and the host at the time of commingling. Mafic magma injected into a cool, viscous, crystalline host may show little evidence of mechanical breakdown, while magma incorporated into a hot, convective, and fluid host may show the greatest amount of mechanical disruption. The exact mechanism for mechanical breakdown of individual enclaves is impossible to determine, although both the "residence time" and the "state" of commingling magmas were probably important processes in controlling the degree of mechanical disruption of
enclaves. Tabular zones of mafic enclaves interpreted as synplutonic mafic dikes may represent later dikes (post emplacement) that became entrained by magmatic flow within the convecting magma chamber.

**FUTURE WORK**

The Precambrian rocks of the central part of the Black Mountains have been mapped in reconnaissance by Anderson (1978) and in this study. This area may be important in evaluating the extent and style of mid-Tertiary faulting. Strata south of the Mount Perkins pluton (Arizona) dip to the west, suggesting that detachment(s) are east-directed, while rocks to the north of the Mount Perkins pluton dip to the east, indicating down-to-the-west detachment (Faulds, 1988). Paleomagnetic studies by Faulds (1988) indicate that the entire Wilson Ridge horst has not been appreciably rotated about a horizontal axis, although intrusive and extrusive rocks of similar age south of Mount Perkins show considerable rotation (>50°). This relationship implies that there may be a major fault (or faults) north of the Mount Perkins pluton and south of the Wilson Ridge pluton. Reconnaissance mapping (this study) revealed at least one north-trending mylonite zone east of the Two B's Mine. Only a detailed study of this area can determine the timing, magnitude, and kinematics of this fault.

The relationship between olivine gabbros that crop out south of the pluton and as pendants within the Horsethief Canyon diorite and the pluton is unknown. These gabbros may represent mafic cumulates of the Wilson Ridge pluton that possibly fed synplutonic mafic dikes. Alternatively, they may be unrelated fault-
bounded Precambrian rocks. A detailed field, petrographic, and geochemical study may determine the origin of these rocks.

A detailed study of the fabric within intermediate rocks of the Teakettle Pass suite may delineate convective cell geometries and/or help constrain mode of emplacement and depth of commingling of the Wilson Ridge pluton.

CONCLUSIONS

1. Both the Horsethief Canyon diorite and intermediate phases of the Teakettle Pass suite plutons were produced by the mixing of large volumes of mafic magma with smaller volumes of felsic magma. Numerous basalt enclaves and tabular inclusion zones in the Teakettle Pass suite are evidence for the mixing of basalt with quartz monzonite to produce the intermediate phases of the suite. Geochemical models confirm that a large mafic to felsic ratio is required to produce intermediate rocks and suggest that fractional crystallization was also an important process.

2. The close similarity in chemistry between enclaves, dikes and basalt flows indicates that enclaves represent a mafic liquid and are probably not wall rock, cumulates, or restite phases. Diorite enclaves are identical to Horsethief Canyon diorite and represent xenoliths.

3. Tabular zones of inclusions may be mafic dikes that formed by repeated injection of basaltic magma into a semi-liquid quartz monzonite host after emplacement of the pluton. Many mafic blobs were plastically deformed, entrained, and mechanical redistributed by vigorous convective stirring to produce
lens-like inclusions and schlieren in foliated intermediate rocks.

4. The Wilson Ridge pluton is a shallow level, hypabyssal to epizonal intrusion that was emplaced passively into an extending crust.

5. The Wilson Ridge pluton has been moderately tilted to the north during mid-Tertiary extension. High-angle normal faulting resulted in at least 1 km of displacement along range-bounding faults. High-angle faults post-date low-angle faults.

6. Interaction between felsic and mafic magma was a complex and ongoing process that probably occurred prior to ascent, during ascent, and following final emplacement of the pluton.

7. In the Wilson Ridge pluton and in other parts of the Lake Mead area, basalt and felsic magma mixed to produce intermediate calc-alkalic igneous rocks prior to and during regional extension (20 to 13.4 Ma) but end-member compositions did not erupt until 4 to 12 Ma when deeply penetrating high-angle faults tapped unmixed magma (Smith et al., 1989). Therefore, there was a delay of nearly 8 Ma between the initial generation of bimodal magmas and bimodal volcanism. Similar mixing processes may operate in other areas of the Great Basin to produce the intermediate rock types so commonly associated with regional extension.
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APPENDIX A

SAMPLE NUMBER - LL88-24
LOCATION - North ridge of Horse Thief Canyon, above large waterfall
PHASE - dike
ROCK NAME - Light grey, sphene bearing, biotite-hornblende-plagioclase phryic andesite.
DESCRIPTION - The rock has a color index of 15. The phenocryst phase comprises 24.8% of the rock, including highly altered, zoned and twinned subhedral plagioclase laths, (11.6%; 1-3mm), strongly pleochroic (green, brown, and yellow) euhedral simple twinned hornblende (11.2%; 1-4mm), and anhedral to subhedral pleochroic (dark brown-red, yellow) biotite (2.0%; 1-2 mm). The groundmass is composed of saussuritized anhedral to subhedral plagioclase laths (60.00%; <1mm), small (<1 mm) anhedral shredded pleochroic biotite (after hornblende, 4.8%), and subhedral pleochroic hornblende (2.0%; <1mm) Accessory minerals include anhedral to subhedral needles of apatite, showing abnormal interference colors (1.0%; <.5mm). The rock contains 4.8% magnetite.

SAMPLE NUMBER - LL88-41
LOCATION - Horse Thief Canyon, .75KM. east of the canyon entrance
PHASE - massive intrusive
ROCK NAME - Medium grained, hypidiomorphic granular, sphene bearing, quartz-kspat-biotite-hornblende-plagioclase diorite
DESCRIPTION - The rock has a color index of 40. Mafic minerals include large subhedral to euhedral honey-yellow sphene which commonly show rhombic cross sections in thin section (3.0%; 1-2mm). Biotite occurs both as primary subhedral crystals (1-2mm), and as secondary anhedral to subhedral fragments after hornblende. All biotite is dark black in hand sample and shows strong straw-yellow and dark brown pleochroism in thin section (total biotite = 14.2%). Hornblende occurs as elongate jet-black subhedral and euhedral crystals (1-3mm), and shows moderate pleochroism with straw-yellow, light green, and dark green colors (22.4%). Quartz crystals are small (<1.0mm) anhedral and interstitial (2.6%). Kspar is anhedral to subhedral interstitial crystals (2.8%; <1.0mm). Plagioclase is subhedral to euhedral and is equant of lath-shaped. Plagioclase commonly shows pericline and albite twinning, as well as oscillatory zoning, with selective sericitization of the calcic cores (49.2%;1-2mm). Apatite occurs as very fine rod-like or needle-like euhedra (2.0%;<.5mm). The rock contains 2.6% opaque minerals.
SAMPLE NUMBER - LL88-43
LOCATION - North ridge of Horse Thief Canyon
PHASE - massive intrusive
ROCK NAME - Medium grained, hypidiomorphic granular, sphene bearing, quartz-kspars-hornblende-biotite-plagioclase quartz monzodiorite.
DESCRIPTION - The color index of the rock is 36. Hornblende shows moderate pleochroism with light green, light yellow, and tan colors, and is subhedral elongate crystals (12.2%; 5-2.0mm). Biotite grains show strong brown and light tan pleochroic colors, and are subhedral crystals (19.4%; 1-2mm). Kspar is anhedral and interstitial (12.2%; 1-2mm) Quartz is also anhedral and interstitial (10.6%; < 1mm). Plagioclase feldspar is subhedral to euhedral laths, (39.7; 1-4mm). Plagioclase shows pericline, albite, and minor carlsbad twinning, as well as oscillatory zoning. Many of the plagioclase laths show selective sericitization of the calcic cores. Composition of the plagioclase was determined using the Michel-Levy method to be Ab 75 (oligoclase).

SAMPLE NUMBER - LL88-59
LOCATION - Waterfall in Dry Falls Canyon
PHASE - massive intrusive
ROCK NAME - Coarse grained, weakly foliated, hypidiomorphic granular, sphene bearing, Quartz-kspars-biotite-hornblende-plagioclase quartz monzonite
DESCRIPTION - The color index of the rock is 37. Mafic minerals include: subhedral to euhedral honey-yellow sphene (3.4%; < 1mm), anhedral to subhedral shredded, strongly pleochroic (straw yellow and red-brown) biotite. Most biotite is 2-3mm, but a few crystals are up to 6mm (total biotite = 14.7%). Biotite occurs locally as interstitial shredded masses between subhedral plagioclase laths. Hornblende is elongate subhedral crystals showing carlsbad twinning and moderately strong (light tan, light green, and dark green) pleochroism. Quartz is anhedral and interstitial (8.0%; < 1mm). Kspar is also interstitial and anhedral, and locally shows micropertithitic texture (8.8%; 5-2.0mm). Plagioclase forms large (1-3mm) subhedral to euhedral laths which are twinned under the albite, pericline, and carlsbad twin laws. Oscillatory zoning is rare in plagioclase. Apatite occurs as an accessory mineral (1.0%) and is quite small (< .5mm). The rock contains 2.0% oxides which are spatially associated with hornblende and biotite.

SAMPLE NUMBER - LL88-45
LOCATION - East ridge of Horse Thief Canyon, 50 meters below the summit of Wilson Ridge.
PHASE - massive intrusive
ROCK NAME - Coarse grained, hypidiomorphic granular, elanocratic, sphene bearing, quartz-kspars-plagioclase-hornblende diorite
DESCRIPTION - The color index of the rock is 60. Biotite occurs only as small (<.5mm) subhedral grains after hornblende and is rare (.60%). Sphene is
subhedral to euhedral crystals (3.0%; < 1mm), and commonly shows rhombic or hexagonal cross sections in thin section. Hornblende is the most abundant mineral phase present (52.6%), and is subhedral elongate, moderately pleochroic (straw yellow, light green, and dark green) crystals, ranging in size from 1-3mm. Kspar and quartz are both anhedral and interstitial crystals. Kspar rarely shows microperthitic texture (2.0%; < 1mm). Quartz is also small in size and abundance (2.0%; < 1mm). Plagioclase is subhedral lath-shaped crystals which commonly show oscillatory zoning, as well as pericline, albite and carlsbad twinning. Plagioclase shows moderate alteration to sericite, with sericitization being greatest at the more calcic core of the zoned plagioclase laths. Opaque minerals are very small and rare (.20%; < .50mm). Apatite is present as small rod-like needles, but is rare (.25%; < .5mm).

SAMPLE NUMBER - LL88-50
LOCATION - False summit on the east side of Mount Wilson
PHASE - massive intrusive
ROCK NAME - Coarse grained hypidiomorphic granular, sphene bearing biotite-quartz-hornblende-kspar-plagioclase quartz monzonite
DESCRIPTION - The color index of the rock is 25 (leucocratic). Sphene is present but rare (.4%) and is anhedral to subhedral, small clusters of crystals (< .5mm). Biotite is dark black, subhedral crystals (1-3mm), and shows strong straw yellow and red-brown pleochroic colors (8.6%). Hornblende forms jet-black needles (1-3mm) and shows moderately strong light yellow, light green, and green pleochroic colors (13.6%). Quartz forms anhedral, interstitial, unaltered masses (14.0%; .5-1.5mm). Kspar is also anhedral and interstitial, although much larger than quartz (.5-3.0mm). Many kspars show very small granophyric intergrowths with quartz (total kspar = 25.8%) Plagioclase forms chalky white laths (1-3mm), and is subhedral to euhedral. Plagioclase is commonly twinned under the pericline, albite, and carlsbad twin laws. Zoned plagioclases are present (approximately 10% of all plagioclase) with only minor amounts of sericitization of the cores and edges. Accessory minerals include only a trace of allanite, zircon, and (.4%) apatite. Oxides are spatially associated with the ferromagnesian minerals, and total 2.6%.

SAMPLE NUMBER - LL88-54
LOCATION - Near the pluton-Precambrian contact on the southwestern margin of the pluton
PHASE - massive intrusive
ROCK NAME - Medium grained hypidiomorphic granular, weakly foliated, sphene bearing quartz-kspar-hornblende-biotite-plagioclase monzodiorite
DESCRIPTION - The rock has a color index of 35 (mesocratic). Sphene is subhedral and rare (.4%; < .5mm). Hornblende is subhedral and commonly shows simple twinning (13.6%; < 1.5mm). All hornblende shows moderate pleochroism (straw yellow, yellow-green, and green). Biotite is anhedral to subhedral shredded fragments, and show strong yellow-orange and red-
brown pleochroism (16.2%; .5-1.5mm). Quartz is anhedral and interstitial (4.4%; <1mm). Kspar is also anhedral and interstitial (4.6%; <1mm). Plagioclase forms large (1-3mm) subhedral to euhedral lath-shaped crystals (52.6%). Plagioclase shows pericline, carlsbad, and albite twins, as well as oscillatory zoning. A foliation is defined by the parallel alignment of elongate amphibole crystals, platy biotite, and feldspar laths. The aligned crystals are surrounded by small anhedral, non-deformed quartz and kspar grains which suggests that the fabric is of magmatic origin. Accessory minerals include prismatic, euhedral apatite (3.2%; <1mm), and trace amounts of zircon (.25%; <.5mm). Opaque minerals are probably magnetite and are spatially associated with hornblende.

SAMPLE NUMBER - LL88-56
LOCATION - Near the pluton-Precambrian contact, on the southwestern margin of the pluton. The sample was taken 1km. northeast of hill 3352.
PHASE - massive intrusive
ROCK NAME - Medium grained hypidiomorphic granular, weakly foliated, sphene bearing biotite-kspar-quartz-hornblende-plagioclase monzodiorite.
DESCRIPTION - The color index of the rock is 30 (mesocratic). Sphene forms subhedral rhombic and hexagonal crystals (1.6%; <1mm). Biotite forms anhedral to subhedral shredded aggregates that show strong straw yellow and orangish red-brown pleochroism. Magnetite (2.6%; .5-1.5mm), is spatially associated with both hornblende and biotite. Kspar is anhedral and interstitial (10.4%; <1mm), as is quartz (15.4%; <1mm). Most quartz occurs as very small (< <.25mm) anhedral grains interstitial between subhedral and euhedral plagioclase, hornblende, and biotite. Plagioclase is subhedral, oscillatory zoned, carlsbad and albite twinned, lath-shaped and equant crystals (49.0%; 1-2mm). A weak foliation is defined by the parallel alignment of the long axes of hornblende and plagioclase, and alignment of biotite plates along the 100 and 010 optical plane. Accessory minerals include anhedral, high birefringent zircon (.8%;,.25mm), and one very small grain of bright red allanite (?). Also present are numerous needle-likeapatite crystals (2.0%; <.5mm).

SAMPLE NUMBER - LL88-60
LOCATION - Entrance of the canyon 2.5km. north of Horsethief Canyon
PHASE - Dike
ROCK NAME - Medium grey, quartz xenocryst bearing, biotite- hornblende-plagioclase phyric andesite
DESCRIPTION - Quartz xenocrysts occur as rounded and embayed, anhedral crystals (1.6%; 1-2mm). Quartz is unaltered and shows undulatory extinction. The phenocrystal phase includes plagioclase, hornblende, and minor biotite. Plagioclase phenocrysts are subhedral to euhedral, chalky white lath-shaped crystals (13.8%; 1-3mm). Plagioclase laths are commonly zoned, as well as twinned under the pericline, albite and carlsbad twin laws. A few plagioclase crystals are rounded and partially resorbed,
suggesting disequilibria. Hornblende phenocrysts are subhedral to euhedral crystals which commonly are diamond-shaped in thin section. Hornblende is simple twinned and moderately pleochroic, showing light yellow, light green, and medium green colors (2.4%; .5-1.5mm). Biotite is rare (.6%), and occurs as strongly pleochroic (red-brown and yellow-orange) colors. Biotite is subhedral and forms crystals .5-1.0mm. The phenocryst phase comprises 17% of the rock. The groundmass is felty and is composed of microlites of subhedral twinned plagioclase laths, anhedral hornblende, anhedral biotite, sericite, and subhedral rods of apatite. Also present are aggregates of chlorite, which occur as four of six-sided pseudomorphs after hornblende. Magnetite occurs as small anhedral crystals dispersed throughout the groundmass (5.8%; <.5mm) The rock also contains trace amounts of subhedral and anhedral sphene (.25%; <.5mm)

SAMPLE NUMBER - LL88-52
LOCATION - Saddle between Mount Wilson and peak 5404
PHASE - Dike
ROCK NAME - Light grey, biotite-clinopyroxene-hornblende-plagioclase phyric andesite.
DESCRIPTION - The color index of the rock is 20. Plagioclase phenocrysts are chalky white, equant or lath-shaped crystals (1.0%; 1mm). Clinopyroxene forms subhedral to euhedral crystals, often showing four or six-sided cross sections, as well as polysynthetic twinning (8.0%; 1mm). Hornblende is euhedral, often six-sided, dark black needles (11.2%; <1.5mm). Hornblende shows strong straw yellow, brown, and dark brown pleochroic colors. Biotite is present as a phenocryst phase (1.6%; 1-2mm), and is strongly pleochroic (yellow and bright red-brown). Biotite is subhedral and somewhat shredded in appearance. The phenocrysts are enclosed in a fine grained (<.5mm) groundmass composed of anhedral hornblende, biotite, plagioclase, and minor (<3.0%) amounts of epidote and sericite (total groundmass = 76%). Also present in the rock is secondary calcite (<1.0%; <.5mm), and minor amounts of magnetite (2.6%; <.5mm).

SAMPLE NUMBER - LL88-42
LOCATION - On top of Wilson Ridge, 25 meters below peak 1421m
PHASE - massive intrusive
ROCK NAME - Coarse grained, leucocratic hypidiomorphic granular, sphene bearing, hornblende-biotite-quartz-ksp-epidote, hornblende-biotite quartz monzonite
DESCRIPTION - The color index of the rock is 11. The principle mafic mineral is biotite, which is shiny black, subhedral to euhedral hexagonal plates. Biotite is moderately pleochroic with straw yellow and light brown colors (9.8%; 1-3mm). Hornblende forms elongate subhedral crystals (1-2mm) and is rare (1.4%). Sphene is the only accessory mineral and is generally subhedral to euhedral; often forming rhombic cross sections in thin section (1.2%; <.5).Quartz is completely unaltered, subhedral equant crystals (16.6%; 1-2mm). Kspar forms anhedral to subhedral equant crystals, and commonly shows micrographic texture with rod-like blebs of intergrown
quartz (total kspar = 26.4; 1-2mm). Plagioclase forms subhedral lath-shaped crystals that commonly show oscillatory zoning as well as pericline, carlsbad and albite twinning (42.2%; 1-3mm). The rock contains 2.4% opaque minerals. Feldspars show only minor alteration to sericite.

**SAMPLE NUMBER - LL88-48**
**LOCATION** - The east end of Horse Thief Canyon, 100m below and due south of peak 1421m.
**PHASE** - Dike
**ROCK NAME** - Green-grey, glomeroporphyritic zircon-sphene-apatite bearing, biotite-hornblende-plagioclase andesite
**DESCRIPTION** - Glomerocrysts are 1-2mm and are composed entirely of pleochroic yellow and green subhedral hornblende (5.6%). Plagioclase occurs as both groundmass and phenocrysts. Plagioclase phenocrysts are subhedral equant of lath-shaped, commonly zoned and twinned crystals (4.6%; 1-2mm). The groundmass is fine grained (.5-1.0mm) and is composed of subhedral zoned and twinned plagioclase (53.6%), subhedral yellow, light green pleochroic hornblende (21.4%; 0.5-1.0mm), anhedral interstitial quartz (1%; <.5mm), anhedral interstitial kspar (<1%; <1mm) and secondary biotite fragments (5%; <.5mm) after hornblende. Biotite shows straw yellow and light brown pleochroism. Accessory minerals include abundant subhedral apatite (4.6%; <.5mm), anhedral clusters of sphene (1.0%; .5mm), and trace amounts of zircon (0.2%; <.25mm). Oxides are probably magnetite, and occur as small blebs that are spatially associated with hornblende and biotite (total oxides = 3%; <.5mm).

**SAMPLE NUMBER - LL88-44**
**LOCATION** - Half way up the northeast ridge above Horse Thief Canyon, below peak 1421m.
**PHASE** - Massive intrusive
**ROCK NAME** - Medium grained mesocratic hypidiomorphic granular, zircon-apatite-sphene bearing, biotite-kspar-quartz-hornblende-plagioclase quartz monzodiorite.
**DESCRIPTION** - The color index of the rock is 30. Mafic minerals include subhedral elongate pleochroic (light yellow, light green green) hornblende (20.8%; 1-2 mm), and anhedral shredded biotite sheets that show moderate pleochroic light tan and brown colors (4.4%; 1mm). Much of the biotite is secondary after hornblende. Sphene is subhedral to euhedral and commonly contains poikilitic inclusions of opaque minerals. The opaque minerals are probably titanomagnetite, and occur as small anhedral blebs (2.4%; <1mm). Kspar is anhedral to subhedral equant of interstitial crystals (8.6%; 1-2mm). Quartz is completely unaltered and is anhedral and interstitial (11.2%; <1mm). Plagioclase is the dominant felsic phase, and forms subhedral, equant or lath-shaped, oscillatory zoned and twinned crystals (48.6%; 1-3mm). Plagioclase has been moderately altered to sericite, particularly in the more calcic cores of the laths. Also present in the rock are trace amounts of sphene (.2%; <.5mm), and subhedral
needless of apatite (1.8%; <.5mm).

SAMPLE NUMBER - LL88-58
LOCATION - .5km. east of the entrance to Horse Thief Canyon
PHASE - Mafic inclusion
ROCK NAME - Dark black, glomeroporphyritic biotite-plagioclase-hornblende basalt
DESCRIPTION - The rock has a color index of 70. Glomerocrysts are composed entirely of fine grained (<.25mm) subhedral to anhedral light yellow and green pleochroic hornblende. The glomerocrysts are 1-2mm in size and are rimmed by dark brown secondary biotite. Plagioclase phenocrysts are entirely or nearly entirely altered to sericite. The relic plagioclases are lath-shaped and subhedral (5.6%; 1-2mm). Rare unaltered and only partially altered plagioclase laths show albite twinning. Plagioclase phenocrysts and hornblende glomerocrysts total 8.7%. The groundmass is very fine grained, felty, and composed predominantly of anhedral to subhedral light yellow and green pleochroic hornblende (53.0%; <.25mm). Also present in the groundmass is anhedral pleochroic beige and brown shredded biotite. Much of the biotite in the groundmass is secondary after hornblende (total biotite = 7.4%; <.25 mm). Groundmass plagioclase laths are locally very weakly aligned (pilotaxitic texture) and are also rarely albite twinned (26.2; <.25mm). Sphene is also a groundmass phase and occurs as anhedral, rounded aggregates (1.4%; <.25mm). The rock contains very small needles ofapatite (1%; <.25mm). Opaque minerals (magnetite?) constitute 4.6% of the inclusion and occur as small (<.50mm) anhedral crystals.

SAMPLE NUMBER - LL88-30
LOCATION - 200 meters south of the pluton/Precambrian contact on the western side of Wilson Ridge, 300 meters east of the range-bounding fault
PHASE - Precambrian basement
ROCK NAME - biotite-quartz-orthoclase gneiss
DESCRIPTION - Quartz is anhedral, undulatory, and commonly occurs as ribbons. Orthoclase is subhedral and commonly altered to kaolin. Orthoclase augen (up to 2 cm) are common. Biotite is anhedral to subhedral. The rock shows a prominent banding, with individual mafic and felsic domains ranging from 0.5 to 2 cm thick. Similar quartzofeldspathic gneiss located 200 meters west of Horsethief Canyon contain 4 to 10% red, subhedral garnets.

SAMPLE NUMBER - LL89-81
LOCATION - occurs as small pods near the southwestern contact of the pluton/Precambrian basement. This rock crops out 1.5 km southwest of Mount Wilson. A small pendant composed of this rock type also crops out on the south-central part of Horsethief Canyon (plate 1).
PHASE - Precambrian (?) intrusion
ROCK NAME - Olivine-clinopyroxene-orthopyroxene-plagioclase gabbro
DESCRIPTION - The rock has a color index of greater than 50 (melanocratic).
The texture of the rock varies from hypidiomorphic granular to poikilitic. Olivine (<10%; 1 mm) is anhedral to subhedral. Orthopyroxene (<10%; <1.5 mm) is anhedral and interstitial, and commonly contains poikilitically included plagioclase laths. Clinopyroxene is equant, subhedral, and is typically 1 to 1.5 mm. Plagioclase (60%; 1 to 2 mm) crystals are subhedral to euhedral and commonly show polysynthetic and simple twinning. Small euhedral plagioclase crystals are typically enclosed in orthopyroxene crystals. Also present is minor (secondary?) biotite and magnetite.

SAMPLE NUMBER - LL88-66
LOCATION - In the bottom of the Horse Thief Canyon, 6 km. east of the entrance to the canyon
PHASE - Mafic inclusion
ROCK NAME - Medium grey, glomeroporphyritic sphene-apatite bearing, hornblende-biotite-plagioclase basalt
DESCRIPTION - The color index of the rock is 42. Plagioclase phenocrysts and glomerocrysts are chalky white in hand sample, and are subhedral, lath-shaped crystals that show albite, pericline and carlsbad twinning, as well as oscillatory zoning in thin section (5.0%;1-2mm). Hornblende is a rare (1%; 1mm) phenocryst phase, and is subhedral elongate crystals. Most hornblende shows moderate yellow, light green and green pleochroism. A few rare hornblende prisms show different pleochroic colors (straw yellow, red-brown, and brown). The rare brown hornblendes are simple twinned and are somewhat shredded in appearance. The groundmass is very fine grained, (<.25mm) and constitutes the bulk of the rock (94%). The groundmass is composed of subparallel, lath-shaped, subhedral plagioclase microlites (pilotaxitic texture) 50%; <.35mm). Groundmass hornblende is light yellow and green in plane light, and forms elongate subhedral and anhedral crystals (9.2%; <.25mm). Biotite in the groundmass is abundant (26.4%) and appears brassy in hand sample (<.25mm). Biotite shows light straw yellow and brown pleochroism, and is anhedral to subhedral. Accessory minerals include very small (<.25mm) subhedral apatite (3.4%), and also small (<.25mm) anhedral sphene (2.0%). Both sphene and apatite are disseminated throughout the groundmass. The rock contains 2.8% oxides (<.25mm).
PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Standard 35mm slides or 17” x 23” black and white photographic prints are available for an additional charge.
DESCRIPTION OF ROCKS

ALLUVIUM - poor to non-indurated sands, angular to subrounded rocks. Canyon diorite, and crystals in stream channels, although range fronts.

MUDDY CREEK FORMATION

Fortification Hill Basalts - thin to alkali-basalt. 4.7 to 5.8 m rocks of the Muddy Creek Formation; 20 meters thick and are largely phenocrysts (<1.0 mm) and subrounded to anhedral.

Sedimentary Rocks Undifferentiated conglomerates are poorly sorted and clast size range from 1 to 5 cm. Precambrian metamorphic rocks of the Muddy Creek Formation include Wilson Ridge granite to obsidian, composed of a single class of clasts and are laterally discontinuous.

WILSON RIDGE PLUTON

Teakettle Pass Suite

Dikes - dikes vary in composition and range in width from coplanar with north-northwest to leucocratic quartz monzonzite. Mafic dikes are dark grey to grey-green amphibole. Phenocrysts include olivine, orthoclase, and biotite.

Quartz Monzonite, Coarse Grain

Pass suite is coarse-grained and leucocratic quartz monzonzite. Ma. Minerals include anorthoclase; zoned and twinned plagioclase; pyroxene; hornblende; biotite; sphene; amphibole; and garnet.
DESCRIPTION OF MAP UNITS

ALLUVIUM - poor to non-indurated sands and gravels. Clasts are predominantly angular to subrounded rocks of the Teakettle Pass suite, Horsethief Canyon diorite, and crystalline Precambrian rocks. Primarily in stream channels, although colluvial deposits crop out adjacent to range fronts.

MUDDY CREEK FORMATION

Fortification Hill Basalts - thin flows of dark grey to black olivine phrylic alkali-basalt. 4.7 to 5.8 Ma flows are intercalated and overlie clastic rocks of the Muddy Creek Formation. Flows are generally less than 20 meters thick and are locally vesicular and brecciated. Olivine phenocrysts (<1.0 mm) are set in a fine-grained pilotaxitic groundmass composed of zoned and twinned plagioclase microlites and subhedral to anhedral orthopyroxene and clinopyroxene.

Sedimentary Rocks Undifferentiated - composed of moderately well indurated conglomerates and coarse sandstones. Conglomerates are poorly sorted and clast supported. Clasts are subangular to angular and range in size from 1 to 30 cm. Clast lithologies include Precambrian metamorphic rocks, phryic andesite and dacite, and Wilson Ridge granite to diorite. Individual beds are commonly composed of a single clast lithology. Beds are typically lensoidal and are laterally discontinuous. Sandstone is locally interbedded with conglomerates and is coarse grained, poorly sorted, and composed of subrounded plagioclase, quartz, orthoclase, and minor silt and clay. Sandstone beds are commonly lenticular and channelized. Some beds show normal grading.

WILSON RIDGE PLUTON

Teakettle Pass Suite

Dikes - dikes vary in composition from granite to basalt. Dikes are tabular and range in width from 0.25 to 20 meters, and are generally coplanar with north-northwest-striking high-angle normal faults. Felsic dikes are leucocratic, granitic, and typically show aplitic or porphyritic textures. Mafic minerals (<10%) include biotite, hornblende and rare sphene. Pegmatite dikes are rare, and are composed entirely of euhedral orthoclase and quartz. Intermediate dikes are andesite and are composed of phenocrysts (10 to 30%) of biotite, hornblende, and plagioclase, set in a fine-grained groundmass composed of plagioclase, biotite, and hornblende. Plagioclase phenocrysts are commonly altered to sericite. Intermediate dikes commonly contain accessory sphene and apatite. Mafic dikes are dark grey to black aphyric and phryic basalt and basaltic-andesite. Phenocrysts include clinopyroxene, olivine, and amphibole.

Quartz Monzonite, Coarse Grained - the dominant phase of the Teakettle Pass suite is coarse-grained, hypidiomorphic granular, and leucocratic quartz monzonite. This phase has been dated at 13.4 Ma. Monzonite includes subrounded quartz, quartz and
Quartz Monzonite, Coal Pass suite is coarse leucocratic quartzite. Minerals in orthoclase; zones subhedral to euhedral acicular apatite, locally porphyritic orthoclase. This mafic enclaves.

Quartz Monzonite, Medium hypidiomorphic groundmass, finer grained than Orthoclase phenocrysts.

Monzodiorite/Quartz Monzonite, granular, mesocrystalline phases locally sheathed by plagioclase laths, minerals include subhedral to euhedral and anhedral intergrown with locally abundant amounts of zircon and diorite enclaves.

Horsethief Canyon Diorite

Diorite and Pegmatitic Diorite hypidiomorphic groundmass, composed of subhedral and zoned subhedral plagioclase, interstitial anhedral hornblende, mesoscopic hornblende prismatic homblende, acicular apatite and prismatic hornblende.

PATSY MINE VOLCANICS

Volcanic Rocks Undifferentiated, phryic andesite and basaltic andesite.

PRECAMBRIAN CRYSSTALLINE GNEISS

Variegated Crystalline gneiss, and medium grained orthopyroxene, olivine-gabbro and diorite enclaves with medium grained orthopyroxene, olivine-gabbro and diorite enclaves, south of the Willamette Valley intrusive contact.
Quartz Monzonite, Coarse Grained - the dominant phase of the Teakettle Pass suite is coarse-grained, hypidiomorphic granular, and leucocratic quartz monzonite. This phase has been dated at 13.4 Ma. Minerals include anhedral to subhedral equant quartz and orthoclase; zoned and twinned lath-shaped euhedral plagioclase; subhedral to euhedral biotite; and subhedral prismatic hornblende. Quartz monzonite contains minor subhedral rhombic sphene, acicular apatite, and trace amounts of zircon. Quartz monzonite is locally porphyritic with phenocrysts of flesh-to-pink-colored equant orthoclase. This phase of the Teakettle Pass suite contains only rare mafic enclaves.

Quartz Monzonite, Medium Grained - fine-to-medium-grained hypidiomorphic granular, leucocratic quartz monzonite. Distinctly finer grained than Tqmc, but is mineralogically equivalent. Orthoclase phenocrysts are rare.

Monzodiorite/Quartz Monzodiorite - medium-grained, hypidiomorphic granular, mesocratic quartz monzodiorite and monzodiorite. These phases locally show a strong mesoscopic foliation defined by aligned plagioclase laths, hornblende prisms, and subparallel biotite. Major minerals include oscillatory zoned and polysynthetically twinned subhedral to euhedral plagioclase, subhedral biotite and hornblende, and anhedral interstitial quartz and orthoclase. Accessory minerals include locally abundant sphene (up to 2.5%), apatite and trace amounts of zircon. These phases typically contain abundant basalt and diorite enclaves. Quartz monzodiorite and monzodiorite are in gradational contact with overlying Teakettle Pass suite quartz monzonite, and are in intrusive contact with Precambrian basement and Horsethief Canyon diorite.

Horsethief Canyon Diorite

Diorite and Pegmatitic Diorite - diorite is medium to coarse grained, hypidiomorphic granular, mesocratic to melanocratic, and is composed of subhedral to euhedral prismatic hornblende, twinned and zoned subhedral plagioclase, subhedral to euhedral biotite, and interstitial anhedral quartz and orthoclase. Diorite contains mesoscopic honey-yellow sphene (2.0 to 4.0%), and euhedral acicular apatite (1.0 to 2.0%). Diorite is locally pegmatitic with prismatic hornblende up to 10 cm in length.

PATSY MINE VOLCANICS

Volcanic Rocks Undifferentiated - predominantly brown and red-brown phric andesite and dacite lava flows less than 20 meters thick.

PRECAMBRIAN CRYSSTALLINE ROCKS

Variegated Crystalline Rocks Undifferentiated - gneiss, amphibolite, gabbro, and minor amounts of biotite and chlorite schist. Banded gneiss is the predominant Precambrian lithology, and is typically composed of quartz, orthoclase, plagioclase, biotite, minor amphibole, local almandine garnet, and hematite. Orthoclase may occur as large augen. Hornblende-plagioclase amphibolite occurs as numerous concordant and discordant tabular bodies and small pods. Olivine-gabbro crops out 1.5 km southwest of Mount Wilson, and is medium grained, poikilitic and granular, and contains clinopyroxene, orthopyroxene, olivine, and plagioclase. Precambrian rocks occur south of the Wilson Ridge pluton where they are in low-angle intrusive contact with massive intrusive phases of the pluton. This
QUADRANGLE LOCATION

UTM GRID AND 1973 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24,000
CONTOUR INTERVAL 40 FEET
CONTOUR INTERVAL 10 METERS
CONTOUR INTERVAL 20 METERS

114°40'00"

1. Detailed Mapping
2. From Mills (1985)
3. From Feuerbach (1986)
4. From Anderson (1978)

DETAIL OF MAPPING

References


GEOLOG
THE WILSON RIDGE PLUTON, COUNTY, ARIZONA

By
Numerous concordant and discordant tabular bodies and small pods. Olivine-gabbro crops out 1.5 km southwest of Mount Wilson, and is medium grained, poikilitic and granular, and contains clinopyroxene, orthopyroxene, olivine, and plagioclase. Precambrian rocks occur south of the Wilson Ridge pluton where they are in low-angle intrusive contact with massive intrusive phases of the pluton. This contact dips gently to the southwest. Roof pendants (≤ 0.2 km²) of Precambrian rock crop out near the southern margin of the Wilson Ridge pluton.

DESCRIPTION OF MAP SYMBOLS

--- CONTACT - dashed where inferred

STRIKE AND DIP OF BEDDING

STRIKE AND DIP OF FOLIATION IN METAMORPHIC AND PLUTONIC ROCKS-

Inclined

Vertical

STRIKE AND DIP OF JOINTS IN PLUTONIC ROCKS-

Inclined

Vertical

LOW-ANGLE NORMAL FAULT SHOWING LESS THAN 30° DIP-
Dashed where inferred; hachures on upper plate.

BASAL CONTACT OF LANDSLIDE MASSES-
Sawteeth on landslide mass.

HIGH-ANGLE FAULT SHOWING GREATER THAN 30° DIP-
Dashed where inferred; Arrow indicates angle and direction of dip. Bar and ball on downthrown side.

FELSIC DIKES

INTERMEDIATE DIKES

MAFIC DIKES