POST-BATHOLITHIC GEOLOGY OF THE VOLCANIC HILLS AND VICINITY, SAN DIEGO COUNTY, CALIFORNIA

A Thesis
Presented to the
Faculty of
San Diego State University

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

by
Robert Fourt
Fall 1979
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Approved by:

[Signatures]

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I would like to dedicate this thesis to G. D. Woodard, who first introduced me to the desert.
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Chapter 1

INTRODUCTION

The Volcanic Hills are located in the southeast corner of San Diego County, seven miles northwest of the town of Ocotillo, California, on State Highway S-2 (see Figure 1). They form low hills bounding the eastern edge of the Jacumba Mountains. They are bordered to the north and east by the Coyote Mountains and to the south by Palm Canyon Wash. The area mapped consists of the northern two thirds of T. 16 S., R. 8 E., and the southern parts of T. 15 E., R. 7 and 8 E. Sweeny Pass and Carrizo Mountain, California, Quadrangles (see Plate I, back pocket).

The Volcanic Hills are part of the low desert province with elevations varying from 920 feet on the desert floor to 2,460 feet, where they join the Jacumba Mountains. The Peninsular Ranges to the west form a rainshadow and precipitation is minimal and restricted to the winter months. Vegetation is sparse and limited to the desert floor and washes and consists of ocotillo, cacti, and a spring burst of seasonal grasses. The Volcanic Hills are part of Anza-Borrego Desert State Park and access is limited to recreational use.

The volcanic rocks are exposed in a series of flat-irons with a gentle eastward-facing dip slope and a steep
FIG. 1--Index map of the Volcanic Hills.
westward-facing slope. Drainage follows the regional north, north-northeast structural grain, except where earlier drainage has been superimposed. The major outlet for the Volcanic Hills is an incised stream channel with several meanders that cut east-west across the structural grain in the northern part of section 11, T. 16 S., R. 8 E. The best exposures are found on the steep strike slopes and in the washes as the gentle dip slopes are usually covered with loose talus and pediment deposits.

The Volcanic Hills lie on the junction between the Peninsular Ranges and the Salton Trough structural provinces. The north-south batholithic belt is truncated on the southeastern flank by the northwest-southeast-trending graben of the Salton Trough. The Volcanic Hills reflect the initial formation of the Salton Trough by the down faulting of the batholith. The graben is controlled by three major fractures related to the San Andreas System. One of the major faults, the Elsinore, with a northwest-southeast orientation passes within 1.5 miles northeast of the Volcanic Hills. The complex faulting in the Volcanic Hills is related in part to this regional fracture. Tectonic activity has continued the Quaternary with Pleistocene sediments involved in the faulting.

Previous Study

Although the early explorers of the Colorado Desert passed through the Volcanic Hills, no record of any geologic work
has been found. H. W. Fairbanks (1892), in his reconnaissance of the region, noted volcanic tuffs and flows that extend northwesterly along the base of the granitic mountains north of Mountain Springs.

W. S. W. Kew (1914) included the Volcanic Hills in his regional geologic map as part of the Coyote Mountains.

In the 1920's, prospectors filed several claims in the Dos Cabezas area for mineral deposits in the basement rocks. Claims were filed for limestone, feldspar, and silica around Dos Cabezas, immediately south of the Volcanic Hills. The Dos Cabezas Mine was developed on the route of the San Diego and Arizona Eastern Railroad for the recovery of limestone used for roofing material, poultry grit, and decorative stone (Tucker, 1925).

L. A. Tarbet (1951) included the Volcanic Hills in his regional map as the western extension of the Coyote Mountains. T. W. Dibblee, Jr. (1954), in his extensive regional mapping, included the Volcanic Hills as a separate geographic and geologic area. His mapping at the regional scale is remarkably detailed showing most of the major outcrops.

F. H. Weber (1963) investigated the crystalline rocks in the vicinity of Dos Cabezas Mine as part of the San Diego County Report for the California Bureau of Mines (Weber, 1963). He reported the occurrence of andesitic lavas that overlie basal conglomerate beds north of Dos Cabezas and in Rockhcase Canyon.
Weber (1963) further suggested that the volcanic rocks exposed in the Volcanic Hills and at Rockhouse Canyon are remnants of flows that originated at Jacumba, seven miles to the south. A generalized geologic map of the Volcanic Hills was completed by C. Preston (1966) as an undergraduate report at San Diego State University.
Chapter 2

ROCK UNITS

Basement Complex

The plutonic and metamorphic rocks of the Peninsular Ranges batholith form the basement rocks in the western Salton Trough. The Volcanic Hills are the downfaulted eastern extension of the Peninsular Ranges and the crystalline rocks are similar to those found at higher elevations to the west.

The metamorphic suite consists of discontinuous roof pendants of coarsely crystalline foliated mica schists, minor pods of amphibolite and quartzite and large blocks of recrystallized limestone. The mica schists are composed of foliated muscovite and biotite flakes with minor porphyroblasts of quartz and orthoclase. The amphibolite is composed of orientated hornblende and quartz crystals with minor biotite grains. The quartzites consist of recrystallized highly sheared quartz crystals.

The metamorphic rocks are found in association with a sheared granodiorite composed of plagioclase, orthoclase, and quartz with minor amounts of biotite. Several highly fractured and altered pegmatite dikes are also found in this unit.
The predominant rock type found in the basement complex is a massive coarsely crystalline unfoliated quartz diorite. The mineralogy consists of euhedral plagioclase phenocrysts in a groundmass of biotite, plagioclase, and minor quartz. The quartz diorite forms the typical spheriodal weathering found in granitic rocks.

Throughout the region, the basement complex is unconformably overlain by either sedimentary or volcanic rocks. Up to 40 feet of relief can be found on the surface of the unconformity.

**Split Mountain Formation**

**Previous Work**

The first mention of terrestrial deposits that underlie the volcanic rocks in the Salton Trough was in the report of W. C. Mendenhall (1910) and restated by W. S. W. Kew (1914), who described interbedded sandstones that were baked bright red by the overlying lava flows. W. P. Woodring (1931) described landlaid reddish and greenish sandstones, conglomerates, and tuffs that underlie the volcanic rocks.

L. A. Tarbet and W. H. Holman (1944) described the terrestrial sediments exposed in Split Mountain Gorge as having four lithofacies: a basal conglomerate, the Fish Creek Gypsum, a marine arenite unit, and an upper conglomerate. They reported Miocene foraminifera in the marine arenite. L. A. Tarbet
(1951) described the sediments that, in part, underlie the volcanic rocks as 2,700 feet of nonmarine fanglomerates containing blocks of metamorphic and granitic rock. He named this unit the Split Mountain Formation for the excellent exposures in Split Mountain Gorge. T. W. Dibblee, Jr. (1954) described the Split Mountain Formation as a coarse basal conglomerate that is present only locally on an irregular erosion surface cut in the older crystalline basement and conformably overlain by younger formations.

G. D. Woodard (1963, 1974) described the section at Split Mountain in detail and redefined the Split Mountain Formation as two formational units. The lower unit was named the Anza Formation and the upper section redefined as the Split Mountain Formation in a restricted sense. The lower unit, the Anza Formation, was described as 1,800 feet of reddish brown arkosic sandstone and interbedded granitic fanglomerate beds. The Split Mountain Formation (restricted sense) was described as having four lithofacies that overlie the Alverson Andesite: a coarse boulder conglomerate, the Fish Creek Gypsum, a sandy micaceous shale unit (the marine arenite of Tarbet and Holman), and a massive grey fanglomerate.

The Anza Formation has not been recognized outside of Split Mountain Gorge. The regional mapping of Tarbet (1951) and Dibblee, Jr. (1954) show the Split Mountain Formation as a basal conglomerate composed of basement clasts and overlain by volcanic rocks.
At the crest of the Peninsular Ranges, a group of volcanic rocks with underlying gravels was described by H. W. Fairbanks (1892) as part of his regional study. W. J. Miller (1935) described the volcanic rocks near Jacumba, California as the Jacumba Volcanics and the underlying sediments the Table Mountain Gravels for exposures on Table Mountain.

Distribution and Thickness

In the Volcanic Hills proper, the Split Mountain Formation is preserved beneath the volcanic rocks as a 30-foot basal conglomerate that lies unconformably upon the basement complex. Further west, in Rockhouse Canyon, 260 feet of conglomerates and sands are preserved beneath volcanic flows (see Plate I, back pocket). These, too, lie unconformably upon the basement complex.

Lithologic Descriptions

In the Volcanic Hills (see Figure 2), the Split Mountain Formation is represented by two lithofacies: (1) an imbricated, unsorted cobble conglomerate with a coarse sand matrix composed of local basement clasts, and (2) a coarse pebbly sandstone. The conglomerate has four distinctive rock types that compose the clast population: rounded cobbles of foliated mica schist, rounded coarsely crystalline quartzite clasts with highly deformed relict bedding, rounded gravel and coarse sand-sized pegmatite fragments, and rounded light grey recrystallized limestone cobbles. The upper unit is poorly cemented by calcite and
FIG. 2 - GENERALIZED GEOLOGIC COLUMN VOLCANIC HILLS

MAP SYMBOLS

- GS Modern Alluvium, stream channel and outwash fans
- OAL Older Alluvium, poorly sorted gravels and sands composed of local basement and volcanic clasts, being downcut by modern streams, 0 to 30 feet
- OT Terrace Deposit, light red conglomerates composed of poorly sorted coarse sands and rounded cobbles of local basement and volcanic rock, 0 to 30 feet
- CCB Canobrake Conglomerate, poorly sorted coarse sands and rounded cobbles composed of local basement and volcanic rock, 0 to 400 feet
- TP Palm Springs Formation, interbedded buff poorly sorted fine sands and silts with dark red well sorted mudstones with fossil wood and reworked microfossils, 20 to 200 feet
- Alverson Canyon Formation
  - TAP Flows, Dikes, and Cinder Deposits, basaltic and hypersthene andesite intrusions, flows, and related cinder deposits
  - TAFU Upper Flows, dark grey platey olivine basalt flows, 30 to 120 feet
  - TAL Volcanic Mudflows, massive chaotic lahars with volcanic clasts up to 15 feet in diameter in a muddy baked matrix, 0 to 60 feet
  - TAS Interflow Sediments, poorly sorted volcanic conglomerates, volcaniclastic tuffaceous sandstones, fine sandstones, and well sorted volcanic mudstones with secondary evaporite minerals, 10 to 40 feet
  - TAFL Lower Flows, light grey platey olivine basalt flows, 40 to 110 feet
- SSM Split Mountain Formation, coarse sand and claystone rip up clast bearing cobble conglomerate composed of local basement and occasional volcanic clasts, 0 to 260 feet
- KOD Basement Complex, recrystallized limestone, mica schists, quartzites, fractured granodiorite, pegmatite dikes, intruded by massive quartz diorite

ROCK UNITS

- GS Modern Alluvium, stream channel and outwash fans
- OAL Older Alluvium, poorly sorted gravels and sands composed of local basement and volcanic clasts
- OT Terrace Deposit, light red conglomerates composed of poorly sorted coarse sands and rounded cobbles of local basement and volcanic rock
- CCB Canobrake Conglomerate, poorly sorted coarse sands and rounded cobbles composed of local basement and volcanic rock
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- SSM Split Mountain Formation, coarse sand and claystone rip up clast bearing cobble conglomerate composed of local basement and occasional volcanic clasts
- KOD Basement Complex, recrystallized limestone, mica schists, quartzites, fractured granodiorite, pegmatite dikes, intruded by massive quartz diorite
contains claystone rip up clasts in a coarse angular sandstone matrix.

Where present in the Volcanic Hills, the Split Mountain Formation has a thickness of 30 feet with the coarse sandstone composing the upper 7 feet. In several outcrops, the Split Mountain is limited to the sandstone facies. No fossils were recovered from this unit.

In Rockhouse Canyon (see Figure 3), the Split Mountain Formation is preserved beneath the volcanic flows. Two units can be found at this locality. The lower unit is composed of poorly consolidated, unsorted angular coarse cobble conglomerate with clasts composed of metamorphic rock and a matrix of decomposed quartz diorite. This unit grades upward into a poorly consolidated imbricated, silty fine sandstone composed of plutonic and metamorphic rock fragments. The lower unit is truncated by an erosional diastem with 1 to 2 feet of relief on the erosional surface.

Above the erosional surface, a poorly consolidated, imbricated, poorly sorted cobble conglomerate composed of local metamorphic basement clasts is found. The matrix is composed of coarse to fine sand-sized fragments of decomposed quartz diorite and angular fine sand-sized reddish-colored fragments of volcanic material. The volcanic rock fragments are composed of felted subparallel plagioclase microlites in a glassy groundmass. The cobbles have a preferred long axis orientation of N10W/25E.
FIG. 3 - GENERALIZED GEOLOGIC COLUMN ROCKHOUSE CANYON

MAP SYMBOL ROCK UNITS

QG Modern Alluvium, stream channel and outwash fans
QUAL composed of local basement and volcanic clasts

QT Terrace Deposit, light red conglomerates composed of poorly sorted coarse sands and rounded cobbles of local basement and volcanic rock, 0 to 30 feet

TCB Canebrake Conglomerate, poorly sorted coarse sands and rounded cobbles composed of local basement and volcanic rock, 0 to 400 feet

Alverson Canyon Formation

TAP Flows, Dikes, and Cinder Deposits, basaltic and hypersthene andesite intrusions, flows, and related cinder deposits

TAS Interflow Sediments, poorly sorted volcanic conglomerates, volcaniclastic tuffaceous sandstones, fine sandstones, and well sorted volcanic mafic tuff with secondary evaporite minerals, 10 to 40 feet

TAFL Lower Flows, light grey platey olivine basalt flows, 40 to 110 feet

TSM Split Mountain Formation, coarse sand and claystone rip up clast bearing cobbles conglomerate composed of local basement clasts, 0 to 30 feet

KOD Basement Complex, recrystallized limestone, mica schists, quartzites, fractured granodiorite, pegmatite dikes, intruded by massive quartz diorite
The upper 15 feet of this unit has been baked a bright red by the overlying basalt flows.

The Split Mountain Formation represents the development of local stream and outwash fans derived from the exposed basement and volcanic rocks. The discontinuous nature of the outcrops indicates that localized channels and fans developed on considerable relief. The large clast size and erosional diastems suggest that the ancient streams were torrential and ephemeral in nature. The depositional environment of the Split Mountain Formation in the Volcanic Hills most closely resembles that of the Anza Formation of Woodard (1974).

The Split Mountain Formation in the Volcanic Hills is thickest in the northeastern exposures and thins rapidly to the west and south where it is missing over most of the region. The Rockhouse Canyon section appears to be a separate channel. The regional drainage was to the east with major localized channels of uncertain orientation.

Alverson Canyon Formation

Previous Work

The volcanic rocks in the western Salton Trough were described by H. W. Fairbanks (1892) as volcanic tuffs, muds, and flows. He also described the volcanic rocks around Jacumba to the south. W. C. Mendenhall (1910) described the volcanic rocks at Coyote Mountain as basal tuffs, volcanic conglomerates, and
red vesicular andesitic lavas with interbedded sandstones. The volcanic rocks were included on the regional geologic map of W. S. W. Kew (1914), who described them as red, green, and blue andesitic extrusives, lavas, and mudflows with interbedded fine sandstones and tuffs.

W. P. Woodring (1931) described the volcanics in Alverson Canyon in the Coyote Mountains as olivine basalt. He cited the petrographic description of the flows by G. H. Anderson as containing "altered olivine phenocrysts in a fine grained holocrystalline groundmass composed of plagioclase laths and augite prisms with magnetite and ilmenite accessory minerals" (Woodring, 1931, p. 15).

W. J. Miller (1935) named the Jacumba Volcanics for the outcrops of volcanic rock found around the town of Jacumba south of the Volcanic Hills. He also mapped the volcanic rocks at the mouth of Devils Canyon and In-ko-pah Gorge as part of the Jacumba Volcanics. These rocks were later included as part of the Alverson Andesite by Dibblee, Jr. (1954).

L. A. Tarbet (1951) formally defined the Alverson Canyon Formation, named for exposures in Alverson Canyon in the southwest of the Coyote Mountains, as at least 700 feet of nonmarine sandstones and conglomerates associated with volcanic flows and tuffaceous sediments. He placed the Alverson as equivalent to and overlying the Split Mountain Formation. T. W. Dibblee, Jr. (1954) defined the volcanic rocks in the western Salton Trough
as the Alverson Andesite consisting of dark brown basic andesitic breccia and tuffs with a thickness of 0 to 700 feet.

The volcanic rocks at Jacumba have been studied by Brooks and Roberts (1954), and Minch and Abbott (1973), who compiled geologic maps of the region. J. W. Hawkins (1970) analyzed several of the Jacumba volcanic units for major and trace element geochemistry.

Distribution and Thickness

The Alverson Canyon Formation forms a linear belt of outcrops along the eastern scarp of the Volcanic Hills and occurs as isolated patches to the west. The eastern belt is highly faulted with the volcanic rocks homoclinal dipping eastward toward the center of the Salton Trough. Several isolated patches occur at the mouth of Lava Flow Wash on the eastern edge of the Hills. In the western half of the Volcanic Hills, the east-west-trending ridges of the basement complex are sporadically capped by the volcanic rocks. A separate exposure occurs just south of the junction of Rockhouse Canyon and Carrizo Canyon. The thickness of the volcanic rocks varies from 15 feet at isolated patches in the west to 250 feet at the crest of the eastern ridge.

Stratigraphic Relations

The Alverson Canyon Formation covers the Split Mountain Formation where present and lies directly upon the basement rocks in the western Volcanic Hills. The Alverson is unconformably
overlain by the Palm Springs Formation and the Canebrake Conglomerate. Remnants of a terrace deposit can be found on the gentle dip slopes of the volcanic rocks in the eastern exposures. The Palm Springs Formation fills the north-south trough that separates the eastern and western Volcanic Hills. The Palm Springs is absent in the western Volcanic Hills and minor patches of the Canebrake Conglomerate cover the volcanic rocks.

The Alverson Canyon Formation in the Volcanic Hills has been subdivided into five units: lower basalt flows, interflow volcanic-sedimentary units, volcanic mudflows, upper basalt flows, plugs, minor flows, and feeder dikes of basaltic and andesitic composition. The lower flows compose the bulk of the volcanic material and are exposed in the eastern ridge and in scattered patches in the west. The interflow sedimentary units are found in a small basin formed by the lower flows and in isolated channels preserved in part by the upper flows. A small intrusive plug cuts the interflow sediments and probably generated the volcanic mudflow. The mudflows thicken southeast of the intrusion. The interflow units are covered in part by the upper flows. Several plugs, flows and feeder dikes, and cinder deposits of basaltic-andesitic composition cut all of the previous units.

**Lower Flows**

The lower basaltic flows that directly overlie the Split Mountain Formation, form the bulk of the volcanic rocks exposed
in the Volcanic Hills. They are well exposed in the eastern scarp (section 14, T. 16, R. 8 E.) and north of Lava Flow Wash along the eastern edge of the Volcanic Hills. They are also found in isolated patches to the west. The rubbly nature of the outcrops and the complex nature of the faulting does not allow individual flows to be traced laterally for any distance. Three to five flows are commonly found in the eastern exposures with an average total thickness of 110 feet. The flows are usually highly fractured, forming a characteristic platey outcrop. The platey nature of the outcrops is suggestive of pahoehoe flow structures, although rapid cooling could also cause the fracturing. However, no columnar jointing was observed at any of the outcrops.

The lower flows are colored a dark medium grey that grades into a mottled greyish red caused by the oxidation of the olivine phenocrysts. Carpet breccias and baked zones can be found separating the flow units. The flows are characterized by a rubbly top and base with massive to platey centers giving an aa texture to the outer surface and a pahoehoe pattern to the interior of the flows. The olivine phenocrysts are commonly altered and replaced, giving the rock a scoriaceous aspect.

The lower flows are composed of basalt and andesite containing partially resorbed olivine phenocrysts that have extensive iddingsite reaction rims. Magnetite is found as inclusions within the olivine crystals. Subparallel euhedral andesine-labradorite (An 50-55) microlites that exhibit flowage around the olivine
phenocrysts make up the intergranular groundmass with interstitial olivine, with augite reaction rims, and hematite stained glass. Secondary calcite selectively replaces some of the olivine phenocrysts. The mineralogy of the lower flows is remarkably consistent varying only in the amount and size of the olivine phenocrysts, the amount of alteration of the interstitial olivine to augite, and the degree of oxidation of the iron bearing minerals (see appendix).

The planar nature and baked zones of individual flow boundaries, oriented platey minerals, and the fractured platey nature of the outcrops indicate a rapidly flowing nonviscous eruption. The consistent mineralogy of the lower flows, and a lack of terrigenous interflow units suggest a common source erupted several flows in quick succession. These flows followed the topographic lows, causing the later flows to migrate around the earlier units.

The lower flows increase in number to the west and north, until they are truncated by a major north-south fault (sections 10 and 14) and buried by the overlying sediments. Further west, the volcanic rocks are found as discrete flows and fault separated patches. An erosion surface is found on top of the eastern exposures.

**Interflow Sediments**

The irregular surface of the lower flows caused several small pockets of terrigenous sediments to be deposited. These
units are preserved as isolated patches on the dip slopes of the eastern scarp and in the depression in the lower flows found in section 14, T. 16 S., R. 8 E. The isolated knoll in the eastern part of section 12 and the knoll in easternmost section 11 have fine sands and volcanic conglomerates preserved beneath the upper basalt flows. This break in the eruptive sequence is used to define volcanic flow packages. The interflow units have been mapped as a single unit based on their stratigraphic position. They are overlain by the volcanic mudflow and the upper basalt flows.

Five lithofacies comprise this unit: a very poorly sorted angular plutonic-volcanic conglomerate, a calcite cemented poorly sorted tuffaceous volcanic-plutonic conglomerate, a very poorly sorted fossil wood-bearing volcanic-plutonic tuffaceous pebbly coarse sandstone, a well sorted dark red gypsiferous mudstone with mixed volcanic-plutonic fine sand-sized lamellae, and a fossil wood-bearing moderately sorted angular fine sandstone. These units are all part of the same depositional system as indicated by the common stratigraphic position and the presence of the tuffaceous clasts not found elsewhere. The size and abundance of the plutonic clasts decreases upward and eastward from the western ridge tops and grades into fine sands in the easternmost exposures (see Figure 4).

In the small basin found at the eastern edge of section 14, the volcanic conglomerate can be traced into the volcanic sandstone
FIG. 4--Interflow units of the Alverson Canyon Formation.
although the actual interfingering is obscured by later intrusions. The tuffaceous sandstone unconformably overlies the mudstone with an irregular contact characterized by scour marks, small channels, and moderate relief. Low angle crossbedding (15 degrees) is found in a large piece of float that has slumped over the mudstone. Large amounts of fossil wood are found weathering out of and in place within the tuffaceous sandstone. The mudstone is limited to a small basin bounded by the lower flows and marked by caliche concretions and irregular seams and secondary gypsum crystals. Washed samples of the mudstone have yielded 160 specimen of fossil oogonia (female reproductive organs) of the green algae charaphyta. The charaphytes have not been previously described and have tentatively been named Chara alversonus. Several unidentified calified shell fragments and a small bone were also recovered. Palynological analysis of the mudstone recovered pollen that was determined to have an age of Oligocene or younger (R. Cullin, 1978, personal communication).

The unconsolidated nature of the mudstone and the torrential nature of the winter rains in the desert has caused the formation of a badland topography where the unit is exposed. The relatively permeable basalts underlying the mudstone have caused extensive piping and the formation of large subsidence features or clastic sinkholes. The tuffaceous sandstone is overlain by basalt flows with feeder dikes and chaotic mudflows.

The associated volcanic conglomerates, tuffaceous sandstones,
and volcanic mudstones represent the formation of seasonal stream, shoreline, and restricted fresh water lakes. The restricted nature of the lake is suggested by the presence of the caliche and gypsum deposits. The presence of the charophytes which are found only in fresh or brackish water environments, often associated with fresh water carbonates, further suggests a restricted fresh water environment (Shimer and Shrock, 1944). The presence of evaporite minerals is indicative of an arid climate where evaporation exceeded precipitation.

The tuffaceous clasts that are found in the volcanic conglomerates are composed of zoned resorbed fractured andesine (An 45) and resorbed hypersthene phenocrysts with hornblende reaction rims and magnetite inclusions. The ground mass is composed of broken shattered plagioclase laths and hematite stained glass shards.

In Rockhouse Canyon, a 10-foot layer of scoriaceous, highly oxidized basaltic rubble is found capping the olivine basalts described earlier. Although none of the distinctive tuffaceous clasts were recovered, this unit occupies the same stratigraphic position as the interflow sediments in the Volcanic Hills. It probably represents the same depositional event. It also is capped by a massive dark grey basalt.

Mudflows

A massive chaotic unsorted volcanic debris flow is found
in the northern wall of Mortero Canyon near the eastern entrance. This deposit forms a distinctive rubbly pitted outcrop with many small recesses formed by the erosion of the larger coherent clasts. Large clasts (up to 8 feet) of a greyish red color are found in a baked crumbly tuffaceous matrix. The basalt clasts are composed of altered olivine phenocrysts with iddingsite reaction rims in a ground mass of subparallel to random labradorite (An 50) microlites with intergranular resorbed olivine extensively altered to augite. Minor calcite replacement is present.

A possible source for the mudflow is the isolated peak in the western part of section 14, where it intrudes and truncates the underlying volcanic gravels (see Figure 4, page 20).

These mudflows are considered to be a local response of the upper flows, where the intrusion erupted into the interflow sediments. The mineralogy of the upper basalt flows is identical to that of the massive basalt clasts found in the mudflow except for the extensive oxidation of the iron minerals in the mudflow clasts. This would reflect the higher water content in the sediments, necessary for the fluid nature of the mudflow.

**Upper Flows**

The interflow sediments are preserved in part beneath basaltic flows with the same mineralogy and chemistry as the lower flows (see Table 1 and appendix). In the northern edge of section 11, volcanic-plutonic conglomerates are overlain by
Table 1

Major and Selected Trace Elements for the Alverson Canyon Formation in the Volcanic Hills

<table>
<thead>
<tr>
<th>Element</th>
<th>Flows</th>
<th>Plugs and Dikes</th>
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<tr>
<td></td>
<td>S-3</td>
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<tr>
<td>SiO₂</td>
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<tr>
<td>MnO</td>
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<td>CaO</td>
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<tr>
<td>K₂O</td>
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<td>0.3</td>
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<td>98.17</td>
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Trace Elements (ppm)

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<th>Plugs and Dikes</th>
</tr>
</thead>
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<tr>
<td>Ba</td>
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<tr>
<td>Cr</td>
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<td>Ni</td>
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<td>Rb</td>
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<td>70</td>
</tr>
<tr>
<td>Sr</td>
<td>1609</td>
<td>910</td>
</tr>
</tbody>
</table>

*Total Fe calculated in Fe₂O₃.
55 feet of platey olivine-bearing medium dark grey basalt with reddish oxidation mottling. This unit is composed of resorbed olivine phenocrysts with iddingsite reaction rims in a groundmass of felted subparallel andesine-labradorite (An 50) micro-lites with intergranular resorbed olivine, augite reaction rims, and interstitial hematite stained glass. Magnetite, often oxidized, is found as inclusions in the olivine phenocrysts and as discrete crystals. The unit is bounded by a 10-foot lower carpet breccia and a scoriaceous upper surface.

Exposed in the isolated knoll that intersects highway S-2 in the northeastern one fourth of section 12, the unconsolidated interflow sediments are capped, with a baked zone, by an olivine basalt flow. The sandstone is overlain with an irregular surface by 50 feet of olivine-bearing basaltic breccia. The clast composition and matrix of the volcanic breccia is identical to that of the basalts found elsewhere in the Volcanic Hills. Discrete clasts up to 1 foot in diameter are randomly scattered in the matrix of the breccia. A rubbly outcrop with a scoriaceous appearance, and a higher level of oxidation distinguish this unit from the overlying platey flows. This autobrecciation can be attributed to the water content of the underlying sands, causing the lower portion of the flow to crystallize into a chill margin or skin that was broken and reworked into the less viscous portion of the flow. Since there is little of the muddy baked nature to the matrix, as found in the mudflow and a limited clast size,
it is likely that the lava was extruded elsewhere and flowed across the water charged sands after eruption. The absence of pillow structures and the presence of a baked zone indicate that little standing water was present at the time of extrusion.

The breccia is conformably overlain by 40 feet of platey, light grey olivine-bearing basalt identical to the lower flows. The oxidation of the phenocrysts gives the flow a slightly scoriaceous aspect.

At the easternmost knoll in section 11, the volcanic conglomerates are covered by a light grey platey olivine basalt. This flow is identical in mineralogy and stratigraphic position to the isolated flow in section 12. These upper flow units could be continuous with the uppermost flows found to the west on the major north-south ridge; however, without the interflow horizons, there is no way to separate the flow units. The upper flows thicken to the east where present, reflecting the same eastward drainage of the other units.

Plugs, Dikes, and Cinder Deposits

Several intrusive feeders and flows cut and cap the earlier flows. The top of Red Hill in section 11 and several other patches on the crest of the main north-south ridge have dark grey massive basalt caps. Minor intrusions of hypersthene andesite can be found on the dip slopes of the main ridge. The dike and plug rocks weather as discrete clasts and readily accept
a desert varnish. The talus from these intrusions form distinctive boulder trails that randomly dot the pediment surfaces.

The feeder dikes are composed of a massive dark grey basalt with altered olivine phenocrysts. Petrographically, they are similar to the flow rocks except for the near random orientation of the plagioclase phenocrysts. The quantity and oxidation of the iron minerals is less than that of the flows.

A prominent feeder dike, flow, and associated cinder cone is found at the mouth of Lava Flow Wash. This intrusion has the same mineralogy as the main flows except for a higher level of oxidation of the iron minerals. It terminates in a cinder deposit with dark purple cinders surrounded by an aphanitic chill zone and a 3-inch baked zone in the surrounding unconsolidated sediments.

The timing of this intrusion is interesting in that the dike and cinder deposit lie on the projected trace of two of the north-northeast-trending faults that slice the lower flows. The feeder dikes for the flow can be found just north of Lava Flow Wash where they are exposed in the lower flows (see Figure 2, page 10). This suggests that the intrusions occurred along the zones of weakness caused by the earlier faulting. Several of the central plugs appear to truncate the complex faulting in section 11. Minch and Abbott (1973) reported similar occurrences in the Jacumba region.

A unique mineralogy is found in several of the smaller
dikes where hypersthenes is the major mafic phenocryst. The andesite is composed of hypersthenes phenocrysts, zoned euhedral plagioclase phenocrysts, and minor euhedral magnetite crystals in a groundmass of andesine microlites with intergranular hypersthenes, magnetite, and hematite stained glass. This rock appears to be a reaction product of the siliceous contamination of the primary olivine basalts.

In Rockhouse Canyon, the uppermost unit that covers the scoriaceous layer consists of several discrete patches of altered magnetite-bearing basalt with a groundmass of iddingsite patches, plagioclase microlites and intergranular anhedral augite and hematite stained glass. This unit also appears to be a reaction product of the contaminated basalts. The presence of magnetite as the major phenocryst is of interest and will be discussed in the section on geochemistry.

Palm Springs Formation

Previous Work

W. P. Blake (1857), as part of the Pacific Railroad Survey, collected mollusks and gastropods at Carrizo Creek. C. R. Orcutt (1890) reported on the "Tertiary Carrizo Creek Beds" as light brown shales and muds. H. W. Fairbanks (1892) described multicolored clay hills near Carrizo Station. W. C. Mendenhall (1910) described a mudstone unit that unconformably overlies shelly layers composed of greenish and reddish shales.
W. S. W. Kew (1914) defined these muds as the Carrizo Creek Formation, with a type section at Carrizo Creek. Kew recognized two members: a lower greenish fossiliferous sandstone-shale unit, and an upper member of grey-greenish to pinkish shales.

G. D. Hanna (1926) redefined the upper division of Kew's Carrizo Creek Formation as a formational unit, the Coyote Mountain Clays. The lower member was subdivided into two new units, the Imperial Formation and the Latrina Sands. W. P. Woodring (1931) separated the brownish-pinkish shales from the underlying greenish muds and defined them as a separate formational unit, the Palm Springs Formation. He described the Palm Springs Formation as poorly consolidated sands and silts of light shades of chocolate brown and brick red which are exposed in the vicinity of the ruins of the old stage station on Carrizo Creek. The name Palm Springs was taken from a spring along the lower part of Vallecito Creek.

L. A. Tarbet (1951) described the Palm Springs as 6,100 feet of interbedded red, buff, and yellow sandstones, and mudstones with fossil wood and sandstone concretions. T. W. Dibblee, Jr. (1954) described the Palm Springs as landlaid arkosic sandstones and red clays that grade into the Imperial Formation and laterally into the Canebrake Conglomerate.

Extensive vertebrate fossil collecting in the Palm Springs Formation was sponsored by the Los Angeles County Museum into the late 1950's. Downs and Woodard (1961) described a Late Pliocene
to Middle Pliestocene (Blancian) age vertebrate fauna from the lower Palm Springs and White and Downs (1961) described a Middle Pliestocene vertebrate fauna from the upper Palm Springs.

G. D. Woodard (1963) described the stratigraphy and paleontology of the Palm Springs Formation at Carrizo Creek and in the badlands to the north. He subdivided the Palm Springs into four members: the Diablo, the Tapiado, the Huesos, and the Vallecito. Woodard described an extensive vertebrate fauna found in sediments interpreted as floodplain, tidal flat, and lagoonal environments.

Merriam and Bandy (1965) determined an Upper Cretaceous source for the Palm Springs based on reworked microfossils. Downs and White (1968) refined the age control of the Palm Springs, based on vertebrates. The Lower Palm Springs was considered to be Late Pliocene (Blancian) and the upper Palm Springs to be Middle Pliestocene (Irvingtonian) age.

**Distribution and Thickness**

The Palm Springs Formation in the Volcanic Hills closely resembles the even bedded, fossil wood bearing, reddish brown mudstones, tan fine sandstones, and buff siltstones of the lower submember of the Diablo Member of Woodard's (1963) classification. Although extensive vertebrate faunas have been found in the Diablo Member, none were recovered from exposures in the Volcanic Hills. The Diablo Member has been dated as Late Pliocene (Blancian)
on the basis of vertebrate fauna (Woodard, 1963; Downs and White, 1968).

The Palm Springs is exposed in the walls of Sweeny Canyon, the southern edge of Jujuba Wash, in isolated patches at the mouth of Lava Flow Wash, and south of Mortero Canyon, where it forms low rolling hills that extend to the southeast. The base of the Palm Springs is covered by valley alluvium and the top is overlain by a terrace deposit or obscured by recent pediment surfaces. The thickness of the exposed Palm Springs varies from 20 to 200 feet. The maximum exposure of 200 feet is found in the walls of Sweeny Canyon.

**Stratigraphic Relations**

The Palm Springs unconformably overlies the plutonic-metamorphic basement complex and the Alverson Canyon Formation. It interfingers with the Canebrake Conglomerate south of Mortero Canyon and southeast of Sweeny Canyon. The Palm Springs is unconformably overlain by a recent terrace deposit in Sweeny Pass and south of Mortero Canyon. The Palm Springs is also found in fault contact with the basement complex, the Alverson Canyon Formation, and the Canebrake Conglomerate.

**Lithologic Descriptions**

The Palm Springs Formation is exposed south of Mortero Canyon in the low rolling hills with gentle slopes mantled with terrace deposits and pediment surfaces. It is composed of a
series of interbedded poorly consolidated fine sandstones and mudstones. The basal unit exposed above the valley fill is a light tan, poorly consolidated, poorly sorted, angular to sub-rounded, micaceous, plant debris-bearing, muddy, very fine sandstone with a thickness of 30 feet. It is conformably overlain by a dusky pale red, very poorly sorted, sub-rounded, very fine sand-coarse silt-sized quartz bearing, mudstone with indistinct parallel laminations. The mudstone has a thickness of 35 feet. Unconformably overlying the mudstone with 1 to 2 feet of erosional relief is a 6 inch lamella of calcite cemented, angular, poorly sorted, coarse sandstone. This sandstone layer grades upward into an angular to subangular, moderately sorted, unconsolidated micaceous very fine sandstone with a thickness of 40 feet. Washed samples of this unit have yielded fragments of the Upper Cretaceous pelecypod *Inoceramus* sp.

The northern edge of the Volcanic Hills is mantled by the Palm Springs Formation. It is exposed at the southern edge of Jujuba Wash in the low hills overlying the volcanic rocks. Forty feet of interbedded dusky red mudstone and light tan fine sandstones are exposed in a small wash on the border of sections 2 and 3. The poorly sorted, very poorly calcite cemented, silty mudstones are conformably interbedded with thin layers of poorly sorted, angular very fine sandstone. No fossils were recovered from this locality.

To the north in Sweeny Canyon, the Palm Springs is
exposed beneath the terrace deposits as a light tan, moderately consolidated, poorly sorted, micaceous, angular, very fine sandstone. Channels of poorly sorted, rounded to subangular clasts composed of metamorphic basement rock cut the sandstone. The sandstones grade southward into a light brown, poorly consolidated, plant debris-bearing, angular silty mudstone. In this locality the Palm Springs has an approximate thickness of 200 feet. No fossils were recovered at this locality.

At the mouth of Lava Flow Wash, a small patch of poorly sorted, fossil wood-bearing, angular silty fine sandstone is preserved above the valley alluvium. It laps up and around a feeder dike, basalt flow, associated cinder deposit.

The clast size and the number and coarseness of channels increase dramatically to the north, suggesting that the regional drainage was north to south. The Canebrake Conglomerate interfingers with the Palm Springs to the north and west of the Volcanic Hills.

Canebrake Conglomerate

Previous Work

The Canebrake Conglomerate was defined by T. W. Dibblee, Jr. (1954) as fanglomerate and grey pebble conglomerate that grades into the Palm Springs Formation. The Formation is named for Canebrake Wash with a type section at the southeastern base of the Vallecito Mountains, 3 miles west of Fish Creek Wash.
T. Downs (1957) collected an extensive vertebrate fauna from the Canebrake north of Vallecito Creek. He dated the Canebrake in that region as Middle Pliocene (Irvingtonian) age. G. D. Woodard (1963) described the Canebrake Conglomerate as a coarse marginal pediment fanglomerate deposit consisting of massive boulder and cobble fanglomerate with a subordinate pebbly arenite.

**Distribution and Lithologic Descriptions**

The Canebrake Conglomerate is magnificently exposed in Sweeny Canyon where 400+ feet of crudely bedded, poorly sorted coarse sand cobble conglomerate composed of local basement clasts are found. Subparallel cobble lenses occur throughout the unit. No fossils were recovered from this locality.

The Canebrake is also found in the southern wall of Mortero Canyon where it is in fault contact with the Alverson Canyon Formation. It is found as a very poorly sorted, very crudely bedded, coarse cobble conglomerate composed of local basement and volcanic rocks. Isolated remnants can be found perched upon basement and volcanic projections above the modern alluvium in the western part of the Volcanic Hills. The clast composition is directly dependent on the locally exposed basement and volcanic rocks.

The Canebrake Conglomerate represents the formation of alluvial fans, pediments, and outwash channels derived from the
uplifted and exposed basement and volcanic rocks. The Canebrake Conglomerate is unconformably capped by a recent terrace deposit. Where present, the terrace deposit is deposited on a near planar surface in contrast to the irregular nature of the Canebrake bedding surfaces.

**Recent Deposits**

**Terrace Deposit**

A recent terrace deposit unconformably overlies the earlier units with a thickness of 2 to 20 feet. In the vicinity of Bow Willow Campground and south through Sweeny Canyon, the terrace is exposed over the Palm Springs Formation and the Canebrake Conglomerate. The contact between the terrace conglomerate and the underlying is unusually sharp and planar. In the Volcanic Hills, the terrace deposit blankets the Palm Springs Formation around Jujuba Wash. South of Mortero Canyon, the conglomerate is directly overlain by the older alluvial surface, and overlies the Palm Springs with an angular unconformity. The contact between the modern alluvium and the terrace deposit is gradational and can be distinguished by the reddish hue of the terrace deposit matrix.

The terrace deposit is composed of rounded clasts of plutonic and metamorphic basement in a matrix of poorly sorted, poorly consolidated, angular plutonic debris. Locally, volcanic clasts can be found within the conglomerate. A slight reddish hue
in the matrix is caused by a minor amount of iron oxide cement. Crude subparallel bedding is present in some exposures.

Woodard (1963) defined a formational unit, the Mesa Conglomerate, for the pervasive terrace deposits that cap the Palm Springs Formation in Carrizo Valley and on the hills to the north. The terrace deposit exposed in the Sweeny Canyon-Volcanic Hills area is probably the southern extension of this unit. Detailed correlation of the units is not possible due to the lack of fossils and the possibility of multiple terrace deposits.

**Alluvial Deposits**

Two generations of alluvium are found in the Volcanic Hills. The older alluvium blankets the volcanic rocks, terrace deposits, and the basement rocks in the western Volcanic Hills. Recent uplift has caused the modern drainage to downcut through the older alluvium and form a modern alluvial surface to the east, between the Volcanic Hills and the Coyote Mountains. The older perched alluvium is easily recognized by its elevated position relative to the modern drainage. The alluvial units are composed of poorly sorted angular clasts of the local basement and volcanic rocks.
Chapter 3

STRUCTURE

The structure of the Volcanic Hills is essentially a series of homoclinal flows that have been complexly faulted by north-south-, north-northwest-, and north-northeast-trending faults (see Figure 5). At least three generations of faulting can be demonstrated by the displacement of differing rock units and the truncation of earlier faults by later faulting.

The earliest faulting occurred in middle Alverson time as the north-south faulting that trends parallel to the crest of the eastern ridge and involves the lower Alverson basalt flows is intruded by later feeder dikes and truncated by the overlying flows. The emplacement of the upper plugs and flows appear to be controlled by zones of weakness caused by the earlier faulting.

A second group of faults occurred after the eruption of the volcanic rocks. North-northwest and north-south oriented faulting displaces the volcanic rocks and the overlying sedimentary units. This group includes the major fracture found in Carrizo Canyon and the Volcanic Hills Fault that separates the eastern flows from the scattered western exposures.

These faults are truncated by a third group of faults that trend north-northeast and give the repeated homoclinal
Elsinore Fault (Dibblee, Jr., 1954)

Legend: — = Fault trace.
Relative sense of movement: up = U; down = D.

FIG. 5--Plan view of faulting in the Volcanic Hills.
flat iron appearance to the eastern flows. Several faults do not involve Cenozoic rock units and the timing cannot be determined.

Unfortunately, there are no piercement points available to determine the slip and the separation of the faulting is all that can be given.

The complex faulting can be related in part to the movements of the Elsinore Fault which has been mapped 1.5 miles to the northeast of the Volcanic Hills (Dibblee, Jr., 1954). The Elsinore Fault is one of the three major fractures that control the graben of the Salton Trough (see Figure 6). The north-northeast-trending faults fit the wrench tectonic model of Wilcox, Harding, and Seely (1973) as high angle (relative to plan view of Elsinore Fault) antithetic faults related to right lateral strike slip movement on the Elsinore Fault. The north-northwest-trending faults appear to be part of the same fault pattern forming low angle or synthetic faults (see Figure 5).

The large north-south-trending fault in Carrizo Canyon does not readily fit into the conjugate shear pattern. It appears to be related to the larger regional faulting found in the Peninsular Ranges structural province.

Faulting has occurred from Middle Alverson time into the recent past. The Mortero Canyon Fault, which places the Alverson Canyon Formation in contact with the Canebrake Conglomerate, has not had a pediment surface developed upon the exposed
FIG. 6--Major tectonic elements of the Salton Trough.

$E$ = Elsinore Fault
$SJ$ = San Jacinto Fault
$SA$ = San Andreas Fault
fault trace. The area is still tectonically active and renewed faulting is highly possible.
Chapter 4

GEOCHEMISTRY

Nine samples reflecting the major flows and intrusive units were analyzed for major and selected trace elements. The samples were prepared by the lithium borate fusion method and run on the San Diego State University Instrumentation Laboratories Atomic Absorption-Emission Spectrophotometer, Model 151. Anne Sturtz aided in the actual operation of the instrument. The oxide values were determined by comparing the emission levels of the rock samples to the emission levels found for United States Geological Survey rock standards. The geochemical data are presented in Table 1, page 24.

Although care was taken to sample the freshest possible flows and intrusive rocks, a wide variation in several of the oxides was found. This variation is not reflected in the petrography of the rocks (see appendix). The variation of the more volatile elements, especially silica and calcium, can be attributed to secondary hydrothermal alteration. As noted earlier, the degree of oxidation of the olivine phenocrysts and the iron minerals varies throughout the volcanic rocks.

The high concentration of olivine and magnetite phenocrysts suggests the possibility of a cumulate crystallization pattern. The early crystallization of the iron minerals indicates
a high oxygen fugacity probably related to a high water vapor in
the original melt. Hawkins (1970) reported early iron crystall-
lization in the Jacumba Volcanics and suggested a high oxygen
fugacity as the cause of the early iron separation.

Experimental high temperature laboratory studies using
a suite of andesitic volcanic rocks of a similar chemical com-
position revealed an early iron separation under saturated water
conditions. At atmospheric pressures, temperatures greater than
1,100 degrees Centigrade, and saturated water content giving a
high oxygen fugacity (Log $f_{O_2}$ greater than -9.5) magnetite is
the first mineral to crystallize (Thompson, 1973). It appears
that a similar process operated in the Volcanic Hills.

The crystallization sequence suggests that the initial
melt was intruded into a magma chamber where partial crystal-
lization of the iron rich minerals occurred prior to extrusion.
The late stage intrusions (sample Bs-1) have hypersthene pheno-
crysts instead of the olivine crystals found in the main flows.
There is also a marked reduction in the iron content in this
unit. This reflects the iron depletion of the residual melt by
the early magnetite crystallization.

In Rockhouse Canyon, the upper basalt flow is character-
ized by magnetite phenocrysts indicative of an early iron
separation.

At this point it is not possible to construct a com-
prehensive model to explain the wide variations in chemistry or
the origin of these unusual basalts, andesitic basalts, and andesites. Hopefully, further research into the chemistry and origin of these volcanic rocks will resolve this problem.
Chapter 5

COMPARISON OF VOLCANIC ROCKS AT JACUMBA AND IN THE VOLCANIC HILLS

The equivalence and common origin of the volcanic rocks at Jacumba and those exposed in the Salton Trough has been suggested by several workers. Miller (1935), in his strip map across the Peninsular Ranges, mapped the volcanic outcrops at the mouth of Devils Canyon and at the mouth of In-ko-pah Gorge as part of the Jacumba Volcanics (see Figure 7). These outcrops are now considered part of the Alverson Andesite of Dibblee, Jr. (1954). The county report of the state Division of Mines further suggests that the volcanic outcrops found in Rockhouse Canyon and the Volcanic Hills are extended remnants of the Jacumba Volcanics. The volcanic rocks found in the Volcanic Hills and Rockhouse Canyon are considered part of the Alverson Andesite by Dibblee, Jr. (1954). The underlying sediments (Table Mountain Gravel-Split Mountain Formation) occupy the same stratigraphic position, i.e., developed on exposed basement and overlain by similar volcanic rocks.

Based on the geochemical evidence, direct correlation of the volcanic rock units is not possible (see Table 2). However, on a larger scale, the stratigraphic record of these localities is remarkably similar and many of the geochemical trends are similar.
FIG. 7—Volcanic outcrops in the western Salton Trough.
Table 2

Comparison of the Geochemistry of the Alverson Canyon Formation and the Jacumba Volcanics

<table>
<thead>
<tr>
<th>Element</th>
<th>Jacumba Volcanics (after Hawkins, 1970)</th>
<th>Alverson Canyon Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Andesitic Basalt (average)</td>
<td>Hypersthene Andesite</td>
</tr>
<tr>
<td>SiO₂</td>
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<td>59.7</td>
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<td>TiO₂</td>
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Trace Elements (ppm)

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*The original analysis of the Jacumba Volcanics included H₂O⁺, H₂O⁻, and P₂O₅ which were not run for the Alverson Samples and omitted from the comparisons.
The geologic sections of Jacumba (Minch and Abbott, 1973) and those of the Volcanic Hills and Rockhouse Canyon, contain a basal conglomerate overlain by olivine-bearing basalts with tuffaceous interflow sediments capped by an upper olivine basalt flow (see Figure 8). The lower flows do not appear similar in the field. Both the Volcanic Hills and Jacumba have volcanic rocks that are intruded by basaltic and hypersthene andesite dikes and plugs. This gross division of the volcanic units is also found to the east in the Coyote Mountains. Radiometric dating of the Alverson Canyon Formation (Ruisaard, 1979) and the Jacumba Volcanics (Hawkins, 1970) reveal a common age of approximately 20 million years. It should be noted that the exotic clasts found in the Table Mountain Gravels are not present in the Split Mountain Exposures in the Volcanic Hills or at Rockhouse Canyon.

The preceding discussion was presented to give background to the problem of stratigraphic nomenclature in the Peninsular Ranges-Salton Trough region. If the apparent equivalence of the Jacumba Volcanics-Alverson Canyon Formation and the Table Mountain Gravels-Split Mountain Formation can be confirmed, the earlier Jacumba-Table Mountain terminology should have priority. However, these units are descriptive of a limited geographic area, while the later Split Mountain-Alverson Canyon terms have been applied over a much larger geographic area. I would suggest in the interest of clarity, that the earlier Jacumba terms be reduced
FIG. 8--Volcanic Hills-Jacumba region correlation chart.
in rank to member status as part of the larger Salton Trough terminology. Thus, the Jacumba Volcanics would become the Jacumba Volcanics member of the Alverson Canyon Formation, and the Table Mountain Gravels would become the Table Mountain Gravels member of the Split Mountain Formation.
Chapter 6

CONCLUSION

The Volcanic Hills represent the initial opening of the landward extension of the Gulf of California-Salton Trough in the Middle Miocene. The breakup of the Peninsular Ranges batholith into isolated blocks and the formation of new oceanic crust in the basin center is reflected in the volcanic rocks and extensive tectonic activity. The Volcanic Hills are on the boundary between the wrench tectonic style of the Salton Trough and the vertical tectonic style of the Peninsular Ranges.

The sequence of events for the Volcanic Hills closely follows J. C. Crowell's 1974 model for the development of a pull-apart basin. As shown in Figure 9, the Volcanic Hills occupy the extreme western edge of the Salton Trough pull-apart basin.

The uplifting of the basin margins and the depression of the interior caused coarse talus to be shed off of the Peninsular Ranges eastward into the center of the newly formed basin (Split Mountain Formation).

The magmatic upwelling postulated by Crowell (1974) in the center of the basin appears to have formed several magma chambers where partial crystallization occurred. These magmas were intruded along preexisting fractures and extruded as patches
FIG. 9--Map of idealized pull-apart Basin (after Crowell, 1974).
of plateau lava flows. This mechanism caused the volcanic rocks to be preserved and exposed around the edge of the basin instead of being buried by later sediment in the center of basin as in Crowell's model.

The later complex faulting related to continued activity on the Elsinore Fault forced the residual melt into the new fractures where it was extruded onto the surface. The continued tectonic activity and downdropping of the basin center allowed the erosion of the exposed basement at the basin margins.

A nontectonic change in base level related to several oscillations of sea level in the Late Pliocene and Early Pliestocene funneled the ancient Colorado River into the Trough where a large delta, tidal flat, and flood plain was built up (Palm Springs Formation). As the ocean receded and the basin continued to subside, the deltaic deposits sealed off the basin interior from the Gulf of California.

To the west, tectonic uplift was occurring that separated the Jacumba region from the rest of the Salton Trough. Late Pliestocene sea level fluctuations caused the removal of most of the Palm Springs Formation and deposition of an extensive terrace deposit.

Continued tectonic uplift of the basin margin has exposed the volcanic rocks from beneath the cover of the younger sediments. Two generations of alluvium testify to the unstable nature of the region as the older alluvium has been uplifted and is being downcut by the modern streams.
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APPENDIX
DESCRIPTION AND PETROGRAPHY OF THE GEOCHEMICAL SAMPLES

The nine volcanic rocks described here range in composition from basaltic to andesitic with most rocks having an intermediate andesitic basalt composition. The mineralogy of the volcanic rocks is remarkably consistent in view of the variations in rock chemistry.

Lower Flows

The lower flows are well exposed in the northern edge of section 11 where the principal drainage has incised a meandering east-west stream channel across the structural grain of the Volcanic Hills. The stream has cut a steep gorge in the lower flows giving excellent exposures. Samples S-3 through S-7 were taken from the northern wall of the gorge where the flows are exposed over the basal conglomerate. The lower flows are characterized by olivine phenocrysts in a microlitic plagioclase groundmass.

Petrographic Descriptions

Sample S-3. This sample is a dark grey basalt with resorbed oliving phenocrysts and iddingsite reaction rims. The groundmass is composed of euhedral subparallel andesine-labradorite (An 45-50) microlites containing flow structures around the olivine phenocrysts. Magnetite is found as an accessory mineral both as discrete phenocrysts and in the groundmass.
The intergranular groundmass is composed of anhedral resorbed olivine crystals with augite reaction rims and interstitial hematite stained glass. Minor secondary silica is found replacing the cores of the larger olivine phenocrysts.

**Sample S-4.** This flow is a medium dark grey basalt with mottled reddish oxidation blotches. It is composed of anhedral resorbed olivine phenocrysts with iddingsite reaction rims and magnetite crystals with oxidized rims. Hematite stained glass is found interstitially in the groundmass. The olivine phenocrysts are commonly found oxidized and altered while the intergranular olivine is quite fresh. A minor amount of secondary silica is found as a pore filler, while the larger olivine phenocrysts have the cores replaced by calcite.

**Sample S-5.** This sample is a dark grey basalt with pale reddish brown oxidation mottling. The resorbed olivine phenocrysts are highly altered with iddingsite reaction rims. Magnetite occurs as inclusions within the olivine phenocrysts and as discrete crystals. The groundmass is composed of euhedral labradorite (An 50) microlites with a subparallel orientation flowing around the phenocrysts. The intergranular matrix is composed of anhedral resorbed olivine crystals with augite reaction rims and interstitial hematite stained glass. Calcite selectively fills the cores of the olivine phenocrysts.
Sample S-6. This flow is a dark medium grey basalt with altered olivine phenocrysts. The subhedral resorbed olivine phenocrysts are rimmed with iddingsite and contain magnetite inclusions. The phenocrysts are found in groundmass of euhedral andesine (An 45) microlites with intergranular anhedral olivine crystals, augite reaction rims, and hematite stained glass. The cores of the larger olivine phenocrysts are replaced by secondary silica.

Sample S-7. This sample is an olivine basalt with reddish oxidation patches. Subhedral resorbed olivine phenocrysts with iddingsite reaction rims are found in a groundmass of euhedral subparallel andesine microlites that show flowage around the phenocrysts. The intergranular constituents are composed of anhedral resorbed oliving crystals with augite reaction rims. Augite is also found as discrete individual anhedral crystals. Hematite stained glass fills the interstices in the groundmass.

Upper Flows

The upper flows can be found at several localities in the Volcanic Hills. In the incised gorge in section 11, the upper flows form a blanket over a series of rubbly interflow units composed of volcanic and plutonic clasts including the unusual tuffaceous clasts found only at this horizon.
Sample S-9. The sample is a medium dark grey olivine-bearing basalt with reddish oxidation patches. Euhedral to subhedral resorbed highly altered olivine phenocrysts with extensive iddingsite reaction rims are found in a groundmass of subparallel labradorite (An 50) microlites showing flowage around the phenocrysts. Magnetite is a common accessory mineral often with an oxidation reaction rim. The intergranular groundmass is composed of anhedral resorbed olivine crystals with augite reaction rims. Augite is also found as individual anhedral crystals. Hematite stained glass is also found in the groundmass.

Crystallization History of the Flow Rocks

The presence of the large olivine phenocrysts indicates that a period of slow crystal growth was followed by the rapid crystallization of the plagioclase microlites, possibly during intrusion. The rapid crystallization of the glassy groundmass, and the limited reaction of the interstitial olivine with the residual melt is shown by the minor amount of augite in the groundmass. The flow structures in the plagioclase microlites are indicative of rapid crystallization after extrusion. The lava was extruded as an olivine-magnetite crystal mush not in equilibrium with the residual melt. A change in the physical conditions, possibly the initial intrusion, allowed the rapid growth of the plagioclase microlites prior to extrusion on the surface. On extrusion, the plagioclase microlites were swept
up in the still liquid lava and crystallized in the oriented flow position. The rapid crystallization of the lava has preserved the unstable olivine crystallites in the groundmass.

The extensive oxidation of both the olivine phenocrysts and magnetite crystals indicates that a considerable amount of water was present during the eruption. The reddish color of the oxidized minerals gives the flows an andesitic appearance.

Intrusive Dikes and Related Flows

Several minor dikes and related flow rocks truncate the lower volcanic units and crop out as localized intrusions and minor flows. Two intrusions cut the interflow sediments in section 14: an olivine-bearing basalt and a hypersthene-bearing andesite. The olivine-bearing basalt intrusion is highly oxidized and appears to have generated the volcanic mudflow. Samples Ad-1 and Bs-1 were taken from these intrusions.

The crest of the eastern ridge is capped by small flow and associated feeder systems. This unit does not exhibit the typical platey outcrop pattern; rather it is a massive basalt showing little or no flow structures. Sample Ub-1 was taken from peak 1681 in western section 14.

Petrographic Descriptions

Sample Ub-1. This rock is a dark grey massive basalt with large oxidized olivine phenocrysts. The subhedral olivine
phenocrysts with iddingsite reaction rims are found in groundmass of subparallel labradorite (An 55) microlites with intergranular olivine, augite, and interstitial hematite stained glass. Augite is also found as reaction rims on the olivine phenocrysts. Several xenocrysts of the host rock can be found with perthitic plagioclase crystals and tourmaline inclusions. Calcite is a secondary void filler.

**Sample Bs-1.** This sample is a massive dark grey glassy andesite. It contains large equant zoned plagioclase phenocrysts as well as resorbed hypersthene phenocrysts. Resorbed subhedral magnetite and highly resorbed anhedral olivine crystals are also found as minor phenocrysts. The groundmass is composed of subparallel to random andesine microlites. Intergranular minerals are anhedral hypersthene, subhedral magnetite, and interstitial hematite stained glass. The iron bearing minerals are oxidized on the crystal edges.

**Sample Ad-1.** This rock is greyish red on fresh surfaces and weathers to a pale red in contrast to the light grey weathering flow rocks. It is composed of equant euhedral zoned plagioclase and euhedral olivine crystals with iddingsite reaction rims. Augite is also found as a reaction product of the olivine. Magnetite crystals with hematitic oxidation rims are accessory minerals. The groundmass is composed of euhedral subparallel labradorite microlites that show flow structures around the
phenocrysts. The intergranular matrix is composed of anhedral resorbed olivine crystallites with extensive augite reaction rims and interstitial hematite stained glass. The iron bearing minerals in the groundmass have been oxidized, giving the rock its reddish cast. Secondary silica is present as a void filler.

**Crystallization History**

The presence of both olivine and the zoned plagioclase phenocrysts indicate an extensive period of slow cooling prior to extrusion. The early precipitation of the iron minerals contemporaneously with the olivine is shown by the magnetite inclusions. A change in the physical conditions of the melt, possibly intrusion, disrupted the slow crystallization and caused the rapid precipitation of the plagioclase microlites. The relict olivine and interstitial glass suggests that the final crystallization of the melt was rapid.

The presence of hypersthene as the major mafic phenocryst in sample Bs-1 is indicative of a more complete equalization of the initial precipitates and the residual melt. The hypersthene is also suggestive of extensive contamination of the residual melt with the silica rich host Peninsular Ranges batholith.

Although these rocks exhibit a similar mineralogy to the lower flows, there are distinct differences. In the field, these rocks have either a light reddish cast or a dark grey massive aspect. In thin section, the longer cooling time is shown by
the primary equant zoned plagioclase crystals and the extensive reaction of the olivine phenocrysts with the residual melt.

These rock types represent the intrusive equivalents of the lower flows. The variations in mineralogy are due to the longer cooling time and extensive reactions with the enriched residual melt.
ABSTRACT

The post-batholithic rocks of the Volcanic Hills are composed of a thin veneer of basal conglomerates of the Split Mountain Formation that are overlain by olivine basalts of the Alverson Canyon Formation. Interflow sediments and mudflows are capped by an upper basalt flow. Basaltic and andesitic dikes cut all previous units.

The volcanic rocks are unconformably overlain by the fine sands and muds of the Palm Springs Formation and the conglomerates of the Canebrake Conglomerate. A terrace deposit unconformably caps the section. Recent uplift has allowed the older sediment to be incised by the modern drainage.

Several generations of faulting have occurred in the Volcanic Hills. Middle Alverson faulting has fractured the lower flows and localized the later intrusions along these zones of weakness. Post-Palm Springs-Canebrake faulting has formed most of the present landforms. Recent faulting is present with fault traces uncovered by modern alluvium.

Volcanic rocks of similar composition and stratigraphic position are found seven miles to the south at Jacumba. A conflict in the stratigraphic nomenclature between corresponding units found in the Peninsular Ranges and in the Salton Trough should be resolved by downgrading the Jacumba-Peninsular Ranges units to member rank within the Salton Trough terminology.