UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

DISTRIBUTION AND PETROLOGY OF THE ANDERSON-COYOTE RESERVOIR VOLCANIC ROCKS

by

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Open-File Report

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TABLE OF CONTENTS

Page

Page

LIST OF FIGURES

Figure		Page

LIST OF TABLES

LIST OF PLATES

Plates

ABSTRACT

The Anderson-Coyote Reservoir volcanic rocks are found within the Santa Clara Formation and unconformably overlie serpentinite, and rocks of the Franciscan assemblage and Great Valley Sequence. They consist of tuffaceous rocks, breccias, and basalt flows approximately 3.5 m.y. in age which are folded and trend parallel to the Santa Clara Valley floor. A deep-seated magma source is inferred by the association of ultramafic xenoliths. In addition, the volcanic rocks form a linear outcrop pattern adjacent to the present Fault zone strongly suggesting that the Calaveras or an ancestral Calaveras may have acted as a conduit for the magma.

INTRODUCTION

The area studied extends from east of Gilroy, California northward along the eastern side of Santa Clara Valley to just north of Anderson Dam (fig. 1). It is located about 24 km (15 miles) southeast of San Jose and is bounded by north latitudes 37°11' and 36°51' and west longitudes 121°40' and 121°27'. The mapped area covers approximately 26 square km (16 square miles) and lies within portions of five 7.5-minute quadrangles: Morgan Hill, Mt. Sizer, Gilroy, Gilroy Hot Springs, and San Felipe (fig. 1).

Although numerous roads provide easy access to most of the area, it is difficult to obtain permission to enter private property. With hopes of future urban development, both absentee landowners and development companies are reluctant to have any persons other than their own geologists do interpretive work.

PURPOSE AND METHODS.--The primary purpose of this investigation was to study the volcanic rocks of the Santa Clara Formation in detail. This was accomplished by: (1) mapping the volcanic rocks at a scale of 1:24,000 with the aid of aerial photographs, (2) construction of geologic structure sections with the aid of drill cores, and (3) collecting samples for microscopic and X-ray studies and chemical analyses. The petrologic study was aided by drill cores which contributed fresher samples for thin sections and chemical analyses. In addition, six step, semiquantitative spectrographic analyses for 30 elements, including mercury, were carried out on selected tuffaceous rocks. This information will be used in a future compilation of mercury concentration in late Cenozoic rocks of the Santa Clara Valley.

PREVIOUS INVESTIGATIONS.--Early studies involving various aspects of the geology in and around the Santa Clara Valley include those of Whitney (1865) and Branner (1907). In 1934, C. F. Tolman, working for the Santa Clara Water

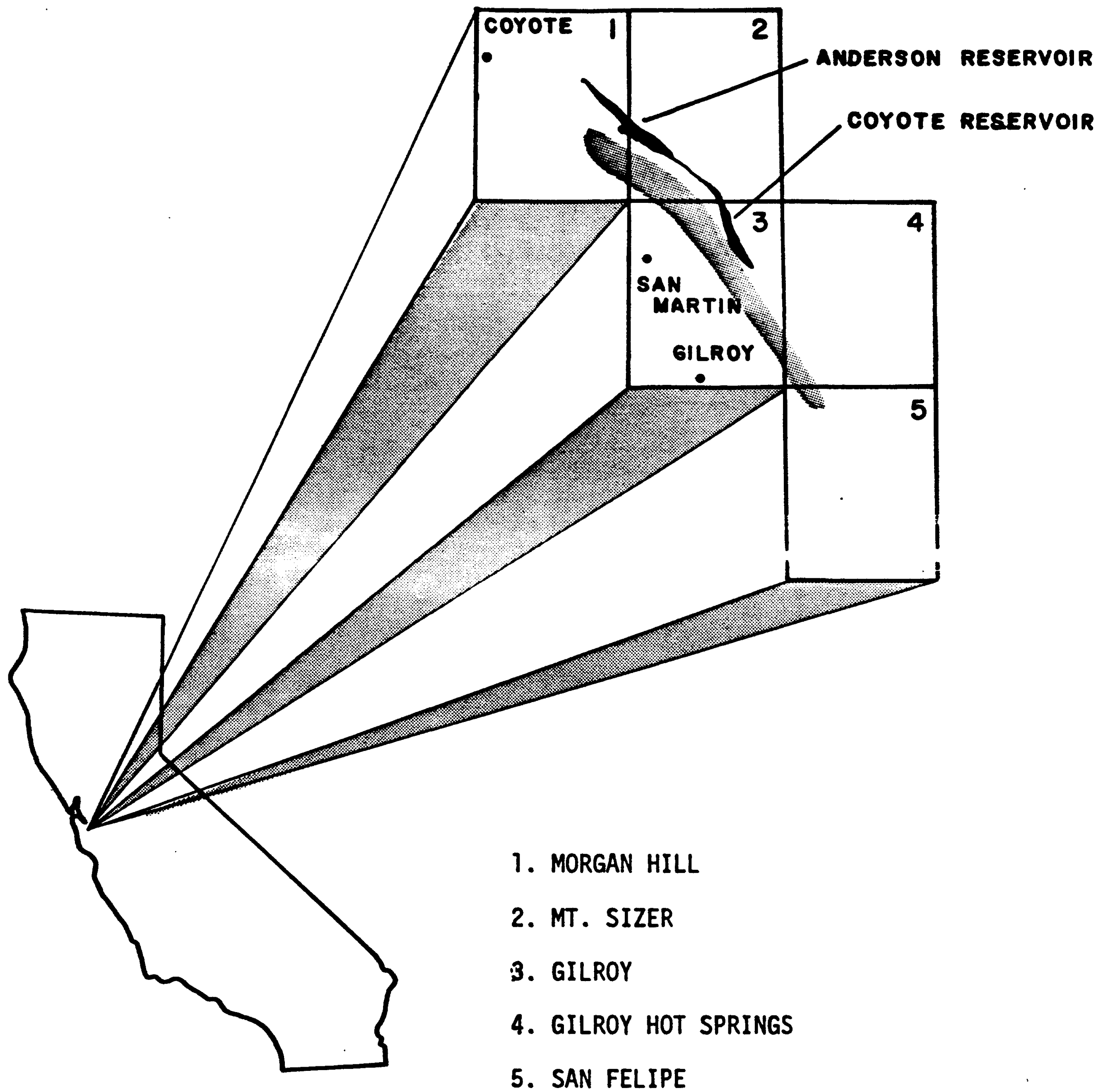


Fig. 1.--7.5 minute quadrangle coverage of the project area.

Conservation District, made investigations around the proposed Coyote damsite. It is in this report that the name Packwood Gravels was first proposed for Plio-Pleistocene nonmarine deposits in the Morgan Hill area. In addition, C. M. Gilbert (1943) first reported Tertiary sediments east of this area.

The Plio-Pleistocene volcanic rocks near Rocky Ridge were first mentioned in thesis studies by Ortalda (1948) and Frames (1955). Ortalda recognized that the olivine basalt was folded with the Packwood Gravels. On the basis of the vesicular structures he concluded that these basalts were of extrusive origin. Frames noted two kinds of volcanic rocks, pyroclastic materials and olivine basalt flows. However, due to the limited exposures, they were not mapped separately.

Several studies which include the project area have been made under the auspices of the U.S. Geological Survey. Dibblee (1973) did reconnaissance geologic mapping, and Nilsen (1972) prepared a landslide map of the South Bay counties, while fault movement along the Calaveras Fault south of Calaveras Reservoir was studied by Radbruch-Hall (1968; 1974). In addition, the National Center for Earthquake Research in cooperation with the Atomic Energy Commission has plotted earthquake epicenters along active faults in west-central California (see Lester et al., 1976). In connection with these studies, Mayer-Rosa (1973) made an extensive study of traveltime anomalies and distribution of earthquakes along the Calaveras Fault zone. Studies made following the 1979 Earthquake are mentioned under the heading of Faulting.

Rogers (1974) studied seismic hazards in Santa Clara County including portions of the thesis area. In addition, C. F. Armstrong and D. L. Wagner (1976) made a detailed geologic investigation of the area northwest of San Felipe Lake.

Other theses covering nearby areas include Carter (1970), Bennet (1973), and Bartsch-Winkler (1976), each of whom mapped directly east of the project area, and Prowell (1974) who studied Tertiary volcanic rocks from the Central Coast Ranges and tried to relate them to the Calaveras and Hayward Fault problem.

Finally, an engineering-oriented study was undertaken in the early 1960's by the engineering firm of Woodward, Clyde, Sherrard, and Associates. In this study, L. S. Cluff, M. Levish, and C. L. Taylor mapped an area near Lake Anderson, but their report has not been made public.

GEOGRAPHIC SETTING.--The area mapped is located along the first ridge east of the Santa Clara Valley. The northwest-southeast trending ridge, with elevations ranging from 400 feet along the valley floor to 1,374 feet along the ridge north of Gilroy Hot Springs Road, makes up the western flank of the Diablo Range.

Although the mean annual temperature is 55°F, it is not uncommon for temperatures to exceed 100°F on hot summer days and to drop slightly below freezing on cold winter mornings. Precipitation averages 20-25 inches per year and falls mostly in the winter months (Rantz, 1971).

The vegetation reflects the semiarid climate as grasses, chamise, manzanita, bay, and live oak are scattered throughout the project area. At higher elevations, a few digger pines are present. Along shady canyons, California Buckeye, poison oak, and several varieties of ferns are found locally.

REGIONAL GEOLOGY

The California Coast Ranges include many separate ranges and structural valleys. The Diablo Range is part of the central Coast Ranges. It is bounded on the west by the Santa Clara Valley and on the east by the San Joaquin Valley, and it extends northwestward for about 160 miles from the Temblor Range to the Carquinez Straits northeast of San Francisco Bay.

The Diablo Range is largely composed of two different rock complexes, the Franciscan assemblage and the coeval Great Valley Sequence. The most common rock types in the Franciscan assemblage are graywacke and metagraywacke, shale, chert, conglomerate, greenstone, and local occurrences of metamorphic rocks of the prehnite-pumpellyite and blueschist facies. However, the Franciscan rocks should not be conceived as a formation with the ordinary coherence and spatial continuity often implied by the classical definition of this term (Page, 1966). Hsu (1968) suggested that the Franciscan is a melange, while others apply the terms complex (Berkland, et. al., 1974) and assemblage (Bailey, et. al., 1964). The term Franciscan assemblage will be used in this thesis.

The Great Valley Sequence, unlike the Franciscan assemblage, is comprised of formations that are coherent and maintain stratigraphic continuity over long distances. These formations exhibit similar rock types, with sandstone and shale predominating and subordinate conglomerate lenses. The rocks are broadly folded, but are otherwise undeformed and offer a distinct contrast with the tectonically broken Franciscan assemblage. A discussion of the complex relationship of the Franciscan assemblage, Great Valley Sequence, and Mesozoic oceanic crust (ophiolite) may be found in Bailey, et. al. (1970).

Although the detailed structure of the Diablo Range is extremely complex, the range is broadly antiformal (Page, 1966; Briggs, 1953) with Franciscan rocks forming the core and Great Valley Sequence and Tertiary strata along the margins.

The major faults in the mapped area along the west side of the range are the Calaveras, Coyote Creek, and Silver Creek faults, all of which are branches of the northwest-southeast-trending San Andreas Fault system.

FAULTING.--According to Atwater (1970), subduction terminated when the North American continental plate overrode first the trench and then the spreading ridge initiating a period of strike slip motion along the margin of North America. Since late Oligocene, the dominant motion of the central California coast has been characterized by horizontal shearing along the transform fault (San Andreas Fault System) separating the Pacific Plate from the North American Plate. Atwater (1970) believes that the current rate of movement at the spreading center is 6 cm per year. This is in contrast to the 3.6 cm per year offset for the San Andreas Fault System northwest of Parkfield, (Savage, J. F. and Burford, R. O., 1973). This apparent discrepancy in spreading rates may be accounted for by stress being relieved along branch faults, such as those in the Calaveras-Hayward Fault zone.

The Calaveras Fault Zone trends northwest-southeast across the area and is characterized by numerous en echelon faults. Previous mappers in the Anderson Reservoir area have subdivided the major strands into three faults: Coyote Creek Fault, Silver Creek Fault, and the main Calaveras Fault.

Coyote Creek Fault.--The Coyote Creek Fault is the first fault east of the Santa Clara Valley floor and acts as the western boundary of the serpentinites in the area mapped. It trends approximately east-west northwest of Anderson Dam, but changes to a southeasterly direction south of the dam. Based on topographic evidence, the attitude of the fault plane undergoes the following changes: (1) northwest of Anderson Dam, the fault plane appears to dip 40-50° east, which is consistent with the 52° dip found by Ortalda (1948), (2) south of Anderson Dam, small topographic deflections of the fault plane to the east as it crosses canyons indicate moderate to high dips to the east, (3) in the vicinity of the south end of Coyote Lake, a pronounced deflection of the fault suggests a low to moderate dip to the east, and (4) south of the Coyote Lake area, the attitude is uncertain because of poor exposures. Ortalda (1948) believes that recent movement has occurred as suggested by conspicuous rift valleys along much of the course of the fault.

Silver Creek Fault.--The Silver Creek Fault extends south from the area mapped by Ortalda (1948) to a point east of Pigeon Point. He shows the fault plane dipping to the west at high angles. The Silver Creek Fault trends S60E northeast of Pigeon Point, but its southeasterly extension was not recognized in the serpentinite. The dip of the fault plane was not determined. However. Ortalda (1948) showed the fault dipping to the southwest at steep angles based on small topographic deflections on the fault plane. The prominence of Pigeon Point and the westward dipping volcanic pile suggest that the western block was uplifted, tilting the volcanic sequence we studied.

Calaveras Fault.--The Calaveras Fault zone crosses the area along a northwest-southeast trend and is chracterized by en echelon faults striking within 15° of the major trend. It generally forms the western boundary for Tertiary and Great Valley rocks exposed east of the fault, as shown by the mapping of Carter (1970), Bennett (1972), and Bartsch-Winkler (1976).

In a study of microearthquakes, Mayer-Rosa (1973) shows a marked concentration of epicenters east of the fault trace which appears to indicate that the fault dips to the east at low to moderate angles. However, Mayer-Rosa believes that the epicenters are anomalously located as a result of a sedimentary wedge altering traveltimes. His recalculations of hypocenters, correcting for the sedimentary wedge, strongly suggests that the fault plane dips at a high angle to the east. The focal mechanism of the August 6, 1979 earthquake is consistent with a vertical, right-lateral, strike-slip fault, (Lee, et. al., 1979).

Historic Movement.--Horizontal movement along the Calaveras Fault during Quaternary and Late Tertiary time is indicated by physiographic features such as small rift valleys, sag ponds, and fault scarps, while offsets of fence lines (Armstrong and Wagner, 1976), damage to the Coyote Dam spillway, offsets of Cochrane bridge girders (Berkland, 1975; Radbruch-Hall, 1968, 1974) and surface faulting that accompanied the 1979 earthquake (Herd and others, 1979; Armstrong, 1979) indicate that movement has continued into historic time and is presently going on.

Displacement rate.--Correlation of the volcanic rocks in the San Felipe Lake area, which lie east of the active fault trace, with similar volcanic rocks across the fault gives a horizontal offset distance that ranges from 5 to 25 km in the last 3.5 m.y. Calculations based on these outcrops give a range of displacement of .14 to .71 cm/yr, very close to the value established by Rogers (1967) of 0.6 cm/yr near Hollister, California. The Anderson-Coyote Reservoir calculations are based on tenous evidence and should be viewed with some reservation. Two problems exist: (1) the uncertainty of correlating rocks across the fault, and (2) offsets along the active trace may have occurred both laterally and vertically on adjacent en echelon faults giving an incomplete record of total displacement and thereby introducing a systematic error in displacement rates. Those rates calculated for the Anderson-Coyote Reservoir area are probably minimum rates. North of the area mapped, creep rates of 1.0 to 1.2 cm/yr have been documented along the Calaveras fault zone by Savage and Burford (1973) and Wesson et al (1974).

Herd (1978) speculates that the long term-rate of slip on the Calaveras fault is on the order of 1.2 to 1.5 cm/yr, almost double the observed rate for the Anderson-Coyote Reservoir area. The difference being made up in catastrophic seismic slip events.

Seismicity.--The general microearthquake (1-M-3) activity of the Anderson-Coyote Reservoir area is shown in figure 2, which indicates that the area is quite active. The lack of many large earthquake suggests that these microearthquakes may act as safety valves releasing strain energy in small quantities and preventing strain build-up.

The 1979 earthquake (M_L = 5.9) was relatively strong and was followed by a sequence of 31 events with magnitudes between 2.4 and 4.4 (Uhrhammer, 1979). According to the U.S. Geological Survey network, the magnitude was 5.7 ± 0.2 with a maximum acceleration of 0.42 g (Porcella and others, 1979). The main shock parameters are as follows:

Origin time: August 6, 1979, $17^h05^m22.3^s$ (±0.1 sec)

Epicenter: $37^o6.7'$N, $121^o32.0'$W (±1 km)

Focal depth: 9.6 km (±2 km)

Magnitude: 5.7 (±0.2) based on 11 readings of signal durations (Lee, Bennett, and Meagher, 1972). The seismographic stations of the University of California gives a Richter magnitude of 5.9 using a 100x Wood-Anderson record at Berkeley (Uhrhammer, 1979).

Cross Faults.--Discussion of cross faults will be limited to those located: (1) adjacent to section 2-2' (plate 1), and (2) perpendicular to section 5-5' (plate 1). Although the two cross faults may truncate the Coyote Creek Fault, it is more likely that they terminate at their intersection with it. The northeast extensions of these faults are probably truncated because

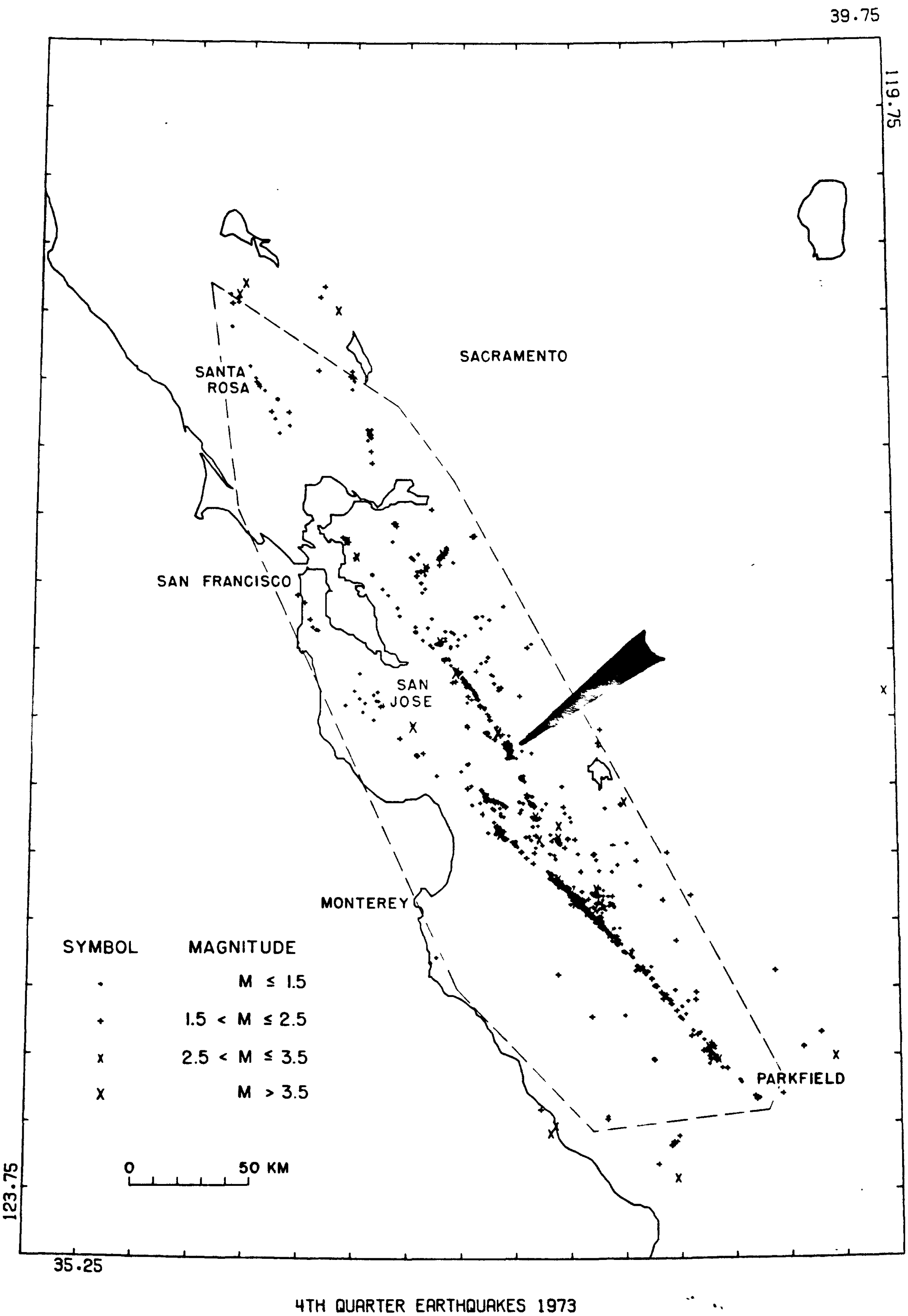


Fig. 2.--Overview of earthquake distribution in northern California; arrow points to thesis area.

of recent movement along the Calaveras Fault. Definite conclusions regarding the fault intersections could not be reached because of poor exposures. There is also the possibility that these may not be faults, but differentially eroded areas exposing different portions of the stratigraphic sequence. Evidence from recent field investigations by Wagner tends to support the non-tectonic juxtaposition of rock units (D. L. Wagner, Calif. Div. of Mines and Geology, oral commun., 1979).

ROCK UNITS OF THE ANDERSON-COYOTE RESERVOIR AREA

Franciscan and Great Valley rocks of Late Jurassic-Cretaceous age and serpentinite form the basement for the overlying Tertiary and Quaternary rocks. The Plio-Pleistocene nonmarine gravels, called Packwood Gravels by Tolman (1934), Crittenden (1955), Ortalda (1948), and Frames (1955) will be refered to as gravels of the Santa Clara Formation near Packwood Valley. For the most part, these gravels unconformably overlie the serpentinite, Franciscan, and Great Valley rocks, but locally they are in fault contact with them. Interbedded with and overlying the Santa Clara Formation are pyroclastic and basaltic rocks. Completing the stratigraphic sequence is older alluvium (Tertiary(?) gravels), Quaternary alluvium, and Quaternary landslides.

Due to the linear outcrop pattern of the volcanic rocks, mapping was confined to a strip 1.2-2.4 km (.75-1.5 miles) wide and 26 km (16 miles) long. The strip-like area limited detailed observations of all units other than the volcanic unit. Consequently, few data were obtained on thicknesses and structure of the serpentinite, Franciscan assemblage, Great Valley Sequence, and Tertiary(?) sediments. Thus, the following is only a brief description of those rock units associated with the volcanic rocks.

SERPENTINITE.--In the past two decades, there has been a revolution in theories concerning the interrelationship of the Great Valley Sequence and the Franciscan assemblage. precipitated by the "New Global Tectonics", many ideas accepted in the 1950's and early 1960's have been replaced by others that are quite different. Serpentinite, once thought to be part of the Franciscan assemblage, is now thought to represent the basal part of the Mesozoic oceanic crust lying beneath the Great Valley rocks and separating the Franciscan assemblage and the Great Valley sedimentary rocks along the Coast Range thrust (Bailey, Blake, and Jones, 1970).

The major outcrop of serpentinite is bounded on its western margin by the Coyote Creek Fault and extends northwestward from East Dunne Avenue to San Jose. Smaller isolated outcrops are found south of East Dunne Avenue and are commonly associated with the Franciscan assemblage.

The ultramafic rocks occur as sheared serpentinite masses, more massive serpentinized peridotites, and silica-carbonate rocks. Although these rock types were not differentiated on the map, they will be discussed separatly.

Sheared Serpentinite Masses.--The highly sheared masses of serpentine make up the bulk of the mapped serpentinite. They are typically greenish-blue, but weather to colors ranging from pale-green to orange. The orange color is caused by oxidation of iron-bearing minerals in the serpentinite. Often these iron minerals appear as fine, black specks contrasting well with the light colored serpentinite rock.

The overall appearance of the sheared serpentinite is dependent on the stage of weathering and intensity of shearing. However, if weathering is slight, even the most intensely sheared serpentine (Lizardite) still has a soapy feel and waxy lustre. As shearing increases, the serpentinite becomes softer and more friable, containing only local pockets of resistant serpentinized peridotite. These islands of resistant material form ridges and areas of bold relief in typically smooth rolling hillsides. They range from a few centimeters to hundreds of meters across. An excellent example may be seen where the Coyote Creek Fault crosses the old East Dunne Avenue. Here, a small fairly resistant serpentinized peridotite body, 3 m in diameter, lies imbedded in a matrix of sheared serpentinite (fig. 3). Much of the shearing is the direct result of faulting, and slickensides are common along fault zones. Chrysotile veins, 0.5 to 0.75 mm in width are found locally along shear planes and fractures.

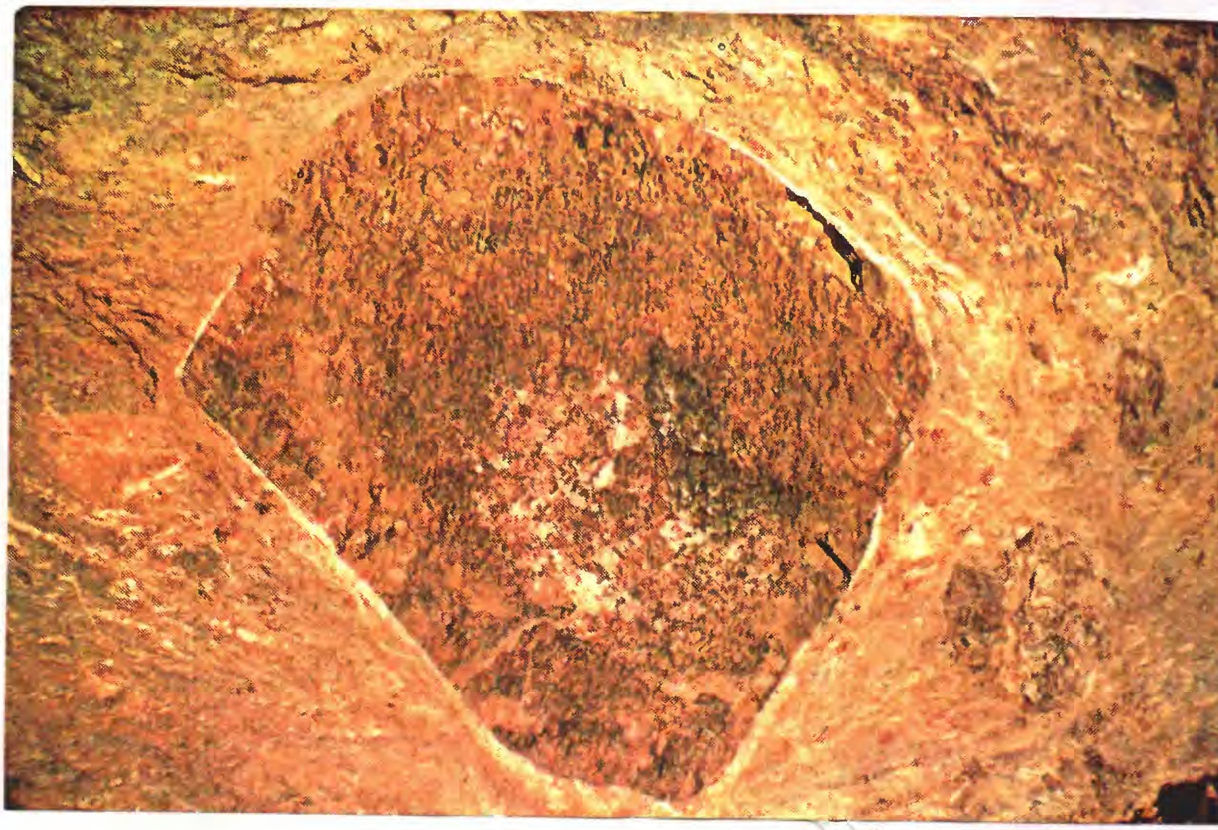


Fig. 3.--Serpentinized peridotite block approximately 3 m in diameter in a matrix of sheared serpentinite. The roadcut is located at the intersection of the Coyote Fault and Thomas Drive (old East Dunne Avenue).

Magnesite ($MgCO_3$) is found associated with the sheared serpentinite. The magnesite ranges from small botryoidal spheres 1-2 mm in diameter to large outcrops which were mined quite successfully during World War II. Bodenlos (1950) believes the emplacement of magnesite is probably a result of hydrothermal activity associated with Pliocene volcanism. According to Bodenlos (1950), solutions rich in calcium carbonate pick up Mg ions at depth and later deposit them as magnesite partially replacing serpentinite. Krauskopf (1967), however, feels that the Mg ions are contributed to the system by weathering of magnesium-rich ultramafic rocks.

Serpentinized Peridotites.--Typical exposures of serpentinized peridotites are blocky and up to 2.5 m across with colors ranging from dark green to orange-brown. From a distance, a boulder-strewn slope may be easily mistaken for basaltic float. On closer inspection, the differential weathering of ultramafic minerals gives rise to a characteristic speckled texture. Olivine, the most susceptible mineral to serpentinization and subsequent weathering, forms a matrix that surrounds bastite pseudomorphs up to 5 mm across after orthopyroxenes. chrysotile veins are common, but are less conspicuous than in the seared serpentinites. They appear as intersecting veinlets 1 to 2 mm in width.

Microscopic examination of three unsheared rocks reveals relict pyroxene grains imbedded in a matrix of serpentinized olivine. Alteration prevents accurate description of their original texture and composition. However, an approximation of mineral percentages places them in the dunite or harzburgite category.

Olivine grins, often completely altered to serpentine, range from 0.5 to 1 mm in diameter. The orthopyroxene pseudomorphs are commonly 1 to 3 mm across and locally exhibit exsolution lamellae of clinopyroxene.

Clinopyroxene also occurs locally as small subhedral grains 1 to 2 mm across. Magnetite is present as scattered euhedral and subhedral crystals and possibly as replacement of spinel. Locally, translucent red hematite rims surround the magnetite. In addition, secondary magnetite and serpentine minerals commonly form a mosaic pattern of intersecting veinlets.

Silica-Carbonate Rock.--Hydrothermal alteration of the serpentinized ultramafic rock to silica-cabonate rock is common throughout the area, but is more pronounced in four localities: (1) west of Pigeon Point, (2) north of Anderson Dam, (3) near the intersection of East Dunne Avenue and Coyote Creek Fault, and (4) south of Roop Road adjacent to the Cinnabar Mine tunnel. The sillica-carbonate alteration of serpentinite helps to form areas of bold relief. Weathered exposures are typically cream-colored when fresh, but oxidation of iron minerals produced orange or reddish-brown staining. Of the hydrothermally deposited minerals, chalcedonic quartz and minor opal are responsible for adding resistance to outcrops. Magnesite is the dominant carbonate with lesser amounts of dolomite, calcite, and aragonite (M. B. Norman, oral commun., 1976). These minerals often occur as intersecting veins and botryoidal masses. When weathering is advanced, the less resistant minerals are removed leaving cellular cavities surrounded by the more resistant silica minerals.

Franciscan Assemblage.--The Franciscan rocks found the area are typical of those described elsewhere in California. Graywackes make up the bulk of the clastic rocks with minor amounts of siltstone, shale, and conglomerate. In addition, small bodies of greenstone, chert, gabbro, and metamorphic rocks are found locally.

Although the Franciscan assemblage underlies much of the area mapped, it is mostly covered by serpentinite, the Santa Clara Formation (particularly the volcanic rocks), and Quaternary landslides. The most extensive exposure lies west of Coyote Lake with smaller outcrops lying northwest and southeast of it. The lack of good exposures, great structural complexity, and the limited area mapped precluded any meaningful estimation of thickness.

Graywacke.--Here, as elsewhere in California, graywacke is the dominant rock type of the Franciscan assemblage. The rocks are gray-green to brownish-green when fresh, but weather to colors ranging from grayish-brown to tan. They are predominantly massive, but beds 2 to 5 cm thick are found locally. Joints often intersect these beds at oblique angles and resemble bedding planes. However, interbeds of shale and siltstone help delineate bedding.

Insepction of four thin-sections of fine- to medium-grained graywackes reveals that the matrix is probably a very fine-grained equivalent of the larger particles or their alteration products. This matrix usually acts as a strong cementing agent which is reflected locally in resistant outcrops. Feldspar is generally the dominant mineral species with percentages ranging from 45 to 60 percent, while quartz makes up 20 to 50 percent of the clasts. In addition, mica, chert, quartzite, and mafic-volcanic rocks were found in varying amounts. Both lithic and feldspathic graywackes were observed, one of which exhibited a crude schistosity reflecting a metamorphic history. No jadeitized graywackes were found.

Shale.--The shales associated with graywackes are dark-brown to black when fresh, but weather to lighter hues. The only exposures or shale observed were those interbedded with graywacke.

Chert.--Chert is limited to one good exposure at a rock quarry northwest of Anderson Dam, but it occurs as float throughout the area. It is typically red or green, but may be chocolate brown, pale gray, buff, pink, yellow, or black. At the quarry, the chert is reddish-brown with layers ranging from 2.5

to 10 cm thick with local thin shale interbeds. In many places, the beds are fractured perpendicular to bedding and the fractures are filled with quartz. Where the chert is weathered, the more resistant quartz veins protrude leaving a criss-crossing pattern along bedding planes. At this locality, the chert is associated with greenstone (altered volcanic rock). Although no reliable attitudes were taken from the contorted beds, the chert-greenstone association may be used as a means of determining "top and bottom." Bailey, Irwin, and Jones (1964) report that the stratigraphic relation of chert overlying greenstone is so common that it provides a guide to the upright or overturned position of a section. Using this criteria, the section adjacent to Anderson Dam is right side up.

Conglomerate.--Conglomerates are rare, but were found interbedded with graywacke at two isolated outcrops. The matrix of the conglomerates appears to be the same as the enclosing graywacke, but petrographic verification was not made. The clasts are well rounded and range from 0.5 to over 4 cm in diameter. They are composed mainly of black chert, volcanic rocks, and minor graywacke. Thickness ranges from 1.0 to 10 cm.

Gabbro.--Small exposures of gabbro were found west of Mud Lake associated with other Franciscan rocks. On unweathered surfaces, colors range from greenish-white to dark olive-green. Oxidation of the mafic minerals, due to weathering, imparts a dull orange color to the rocks. In addition, less resistant pyroxenes weather and leave small rectangular cavities which give the rock a pitted appearance.

Hand lens inspection of two samples of gabbro showed them to consist mainly of plagioclase and pyroxene with trace amounts of spinel (and olivine?). Both samples are medium grrained and have a hypidiomorphic granular texture. The pyroxenes average 1 to 2 mm in length, while plagioclase laths are somewhat smaller. Sample JKN-210 contains 65 to 70 percent plagioclase and 30 to 35 percent pyroxene, while sample JKN-212 contains 50 to 55 percent plagioclase and 45 to 50 percent pyroxene. Based on color index (CI), these samples probably represent end members of the gabbroic rock sequence found in this area.

Greenstone.--The largest exposures of greenstone lie northwest and southeast of Anderson Dam. Both localities have been quarried for use as riprap. The greenstones are shades of green, but weather to a gray-green and orange. They are aphanitic and cut by numerous calcite and quartz veins. Many of the large calcite veins have well formed crystals ranging from 0.5 to 1.5 cm across. Extensive shearing and mylonitization of the rocks reflects the proximity of the Coyote Creek Fault. Slickensides are common, but no statistical analysis of slip-plane orientation was made.

Ophiolite Sequence(?).--Rocks which may represent portions of a dismembered ophiolite sequence are exposed 0.3 km northwest of Anderson Dam. According to Bailey and others (1970), a typical succession from the top downward consists of chert, lavas, gabbro, and serpentinized ultramafic rock. In this area, altered volcanic rocks (greenstone) locally showing pillow structure are overlain by well-bedded reddish-brown chert. In contact with the chert is well lithified graywacke which is in fault contact with serpentinite. Gabbroic rocks, usually associated with an ophiolite sequence, are absent at this locality, but they occur as float 4 km to the southeast, adjacent to the Coyote Creek Fault.

Metamorphic Rocks.--The largest concentration of metamorphic rocks is found approximately 1.5 km west of Mud Lake. Smaller exposures are found elsewhere in the Franciscan terrain, but they are quite rare. Distinct outcrops are nonexistent, but chlorite, glaucophane, and almandine amphibolite schists were found as float.

Knoxville Formation/Great Valley Sequence.--The name "Knoxville Beds" was first used by White (1885) in describing Buchia-bearing beds located in the Knoxville mining district of the Morgan Valley quadrangle, California. Subsequent use by Anderson (1902) restricted the name Knoxville to the lower Buchia piochii-bearing beds of Late Jurassic (Tithonian) age in the Sacramento Valley area. In the south San Francisco Bay area (Mt. Hamilton quadrangle), Crittenden (1951) reported thin-bedded fossiliferous shales of Late Jurassic to Lower Cretaceous age and named them the Berryessa Formation (a formation now considered part of the Great Valley Sequence). Ortalda (1949), Frames (1955), Carter (1974), Bennet (1973), and Bartsch-Winkler (1976) have extended the Berryessa Formation from Crittenden's type locality to the Anderson-Coyote Reservoir area. However, for this study the sequence of thinly bedded dark shales containing Buchia piochii were mapped as part of the Knoxville Formation, whereas the nonfossiliferous shales, sandstones, and conglomerates were mapped as part of the Great Valley Sequence.

Knoxville Formation.--Rocks mapped as Knoxville Formation ar restricted to thin slices within the Calaveras Fault zone adjacent to Coyote Reservoir. These beds contain the small pelecypod Buchia piochii (identified by D. L. Jones, U.S. Geological Survey, Menlo Park, California) which weathers from dark brown shales along Roop Road. Buchia piochii is a diagnostic Late Jurassic (Tithonian) macrofossil in the Knoxville Formation, so assignment of these dark shales to the Knoxville is both faunally and lithologically sound. However, other somewhat similar but unfossiliferous shales, siltstones, and sandstones were mapped as part of the Great Valley Sequence. This designation does not preclude the presence of unrecognized Knoxville rocks.

Great Valley Sequence.--These beds generally strike northwest-southeast and dip at moderate to steep angles to the east. The mapped portion of the Great Valley Sequence consists of thin-bedded shales, silty-shales, siltstone, sandstones (graywacke), and minor limestone nodules. This sequence shows evidence of intensive folding with joints and fractures oblique to bedding. Although shales and sandstone units are locally homogeneous, they often contain interbeds of other rock types. In addition, these rocks show rapid lateral lithologic and structural variations.

Since only a small section of Great Valley rocks was mapped, no thicknesses were measured. However, Ortalda (1948) estimated a minimum thickness of 3,700 feet of the Berryessa Formation in the lower Coyote Creek area. Frames (1955) states that 8,800 feet of section is exposed west of Hyde Peak. In addition, Frames believes that the complete Late Jurassic to Cretaceous section may be more than 10,000 feet in thickness.

Shale, silty-shale, and siltstone.--Shale, silty-shale, and siltstone are the dominant rock types and comprise 70 percent of the Great Valley Sequence. The shales are well-bedded with beds ranging in thickness from 1 to 12 cm. Siltstones commonly form beds slightly thicker, and are locally massive. The shales occur in two varieties: a dark brown, fine-grained type, and a tan silty variety which grades into a siltstone. Both types weather forming a uniform soil horizon. In areas where weathering is not advanced, the darker shales crumble and form small light-brown rectangular fragments 1 to 3 cm+ across. Soils developed on silty-shales and siltstones often weather to pinnacle-shaped spires similar to those found in "Badlands" topography.

Limestone.--Associated with shales are local occurrences of limestone nodules. They were not recognized within the shale but found as float. They appear to be restricted to a particular horizon and may be followed along strike for short distances. They are dark gray on fresh surfaces, but weather to colores ranging from light orange to off-white and contrast well with the light brown soil derived from the shale unit.

Sandstone.--The sandstones are predominantly massive, but are locally thinly bedded. Many outcrops are covered with a gray-green crustose lichen. However, fresh surfaces are brown, gray-brown, and tan, but weather to colors ranging from light-brown to an orange tan. the sandstones are friable to extremely resistant. Many of the darker sandstones are more resistant and stabilize small ridges which parallel the Santa Clara Valley. Lenses may be followed along strike but vary is thickness and often pinch-out abruptly. Associated with the sandstones are minor conglomerate lenses with pebbles of plutonic, volcanic and sedimentary rocks.

Twenty sandstone samples were differentially stained for plagioclase and potassium feldspar. They appear to range from feldspathic sandstones to graywackes. About 10 percent of the samples have a calcareous cementing agent while the remaining 90 percent are found by varying amounts of clay. They are fine to medium grained with angular to subrounded grains. An average percentage and range of mineral species from the stained samples is given below:

MINERALS	AVERAGE PERCENGATE	PERCENT RANGE
Quartz..............................	55%	25 to 85%
Potassium feldspar..................	16%	0 to 40%
Plagioclase.........................	26%	5 to 70%
Biotite and lithic fragments........	3%+	0 to 10%

Stratigraphic Relations.--The base of the Knoxville Formation was not observed, but the section that contains the Buchia piochii may represent strata close to the base. The Knoxville Formation and Great Valley Sequence is everywhere separated by a fault from the coeval Franciscan assemblage. In addition, serpentinite is in fault contact with the Knoxville Formation but locally may be in depositional contact with it (section 6-6', plate 1). Other than older alluvium, minor volcanic rocks and landslides, contacts with Tertiary formations are absent.

Tertiary Gravels(?) (Quaternary Alluvium).--Alluvial material which possibly predates the Pliocene volcanic rocks was mapped as a continuous blanket east of the Calaveras Fault and southwest of Coyote Lake. Locally, it is well-bedded, srikes approximately north-south, and dips at low to moderate angles to the east. The subangular cobbles and pebbles are set in a loosely consolidated matrix of silt and sand. Mineralogically, the pebbles and cobbles are sandstone, shale, chert, and serpentinite. Plio-Pleistocene volcanic rocks are absent from the clastic sediments, and this may indicate a pre-Pliocene age, or these sediments may have been derived from a drainage area that did not supply volcanic debris.

Adjacent to Canada Road, a small outcrop of conglomerate (locally brecciated) unconformably overlies the Great Valley Sequence. A visual estimation of clast type is sandstone 85%, black shale 5%, miscellaneous 1%, with a sand and silt matrix comprising 9% of the rock unit.

Santa Clara Formation.--Nonmarine gravels and sands of Late Cenozoic age in Santa Clara Valley were first called the Santa Clara Formation by Cooper (1894). Branner and others (1906) applied the name Santa Clara Formation to Plio-Pleistocene strata near Santa Cruz in their study of the 30-minute Santa Cruz quadrangle. Subsequent mapping has enabled investigators to correlate many of these nonmarine sedimentary facies in areas in and around the Santa Clara Valley. For an overview of current literature, see Helley and Brabb (1971) and Cummings (1968).

Cummings (1972) believes that the Santa Clara Formation is composed of numerous lithologic facies that may or may not have formed a continuous blanket. Isolated areas of clastic sediments deposited during the Plio-Pleistocene may be considered part of the formation on the basis of stratigraphic position and clast composition.

Tolman (1934), in his study of the Coyote Dam site, first proposed the name Packwood Gravels for a sequence of nonmarine clastic sediments in the Morgan Hill area. Ortalda (1948) and Frames (1955) adopted the name for a sequence of relatively unconsolidated sediments found west of the Anderson-coyote Reservoir area. However, Dibblee (1972) mapped this unit as part of the Santa Clara Formation. This terminology will be adopted for this investigation, and the rocks are herein referred to as gravels of the Santa Clara Formation.

The Santa Clara Formation crops out west of the Calaveras Fault and lies in both fault contact and unconformable contact with the Mesozoic rocks. This sequence is folded into small synclines and anticlines that trend northwest and southeast adjacent to the valley floor.

Outcrops are poor except in recent roadcuts and along some canyon bottoms. The clastic sediments generally form low rolling hills but may be easily distinguished by pebbles and cobbles that weather from gravel layers within the unit. Colors range from off-white to various shades of brown. However, adjacent to the Coyote Fault in the vicinity of the old East Dunne Avenue, the rocks are a distinct orange-brown. Here, the Santa Clara Formation is in fault contact with serpentinite which may contribute ferric iron from weathering of mafic minerals.

The gravels of the Santa Clara Formation consist of gravel interbedded with sand, silt, clay, calcareous lenses, and a sequence of volcanic rocks which will be discussed in detail in another section. Generally the sediments are loosely consolidated, but well lithified equivalents are found locally. The gravels consist predominantly of clasts of the underlying Mesozoic rocks; clasts of the following types are found: chert of many colors, graywacke, shale chips, serpentinite, greenstone, vesicular and massive basalt (intraformational), miscellaneous volcanic rocks (rhyolite and andesite), plutonic rocks (granite and gabbro), and metamorphic rocks (glaucophane and chlorite schists). These pebbles and cobbles are subangular to subrounded sand grains. Quartz is the dominant mineral in the matrix (40 to 70 percent) with feldspar composing 10 to 30 percent, and lithic fragments usually forming less than 10 percent of the gravel.

Age and Correlation.--These gravels represent continental deposits resulting from a strong Pliocene uplift. They may or may not be time-corelative with other Plio-Pleistocene continental deposits such as the San Benito and Livermore gravels. Ortalda (1948) believes that the southern extension of the (Packwood) Santa Clara Gravels may represent the northern extension of the San Benito Gravels found in the Hollister quadrangle. The lack of fossil evidence precludes a relative age assignment in the southern Bay area. Along East Dunne Avenue, a basalt flow is interbedded with the Santa Clara Formation. An attempt to date this flow radiometrically failed, but Sarna-Wojcicki (oral commun., 1973) dated a basalt flow southwest of coyote Reservoir at 3.5 m.y. The relative position of the dated sample within the stratigraphic section was not determined because of extremely poor exposures. Its geographic location is diagrammatically indicated on the geologic map (plate 1) with the symbol .

OLDER ALLUVIUM AND QUATERNARY ALLUVIUM.--Both of these units are similar lithologically and consist of gravel, sand, silt, and clay. They differ, however, in that the older alluvium is dissected by erosion and locally well lithified.

QUATERNARY LANDSLIDES.--Quaternary landslides are quite common within the area of study. They are not restricted to any particular rock unit, but occur most commonly on serpentinite, the Santa Clara Formation. Generally, the landslides are characterized by hummocky and jumbled topography. In those areas lacking hummocky topograhy, tilted fence lines and tilted trees helped delineate downward movement of surficial material (fig. 4).

The largest landslide, approximately 2 square km in area and located 1.5 km west of Coyote Dam, has moved a portion of the Santa Clara Formation and the underlying Franciscan assemblage southwestward forming a protruding lobe onto the valley floor.

Fig. 4.--Tilted fence lines attest to the downward movement of surficial material, Coyote Creek area (II).

ANDERSON-COYOTE RESERVOIR VOLCANIC ROCKS

INTRODUCTION.--Volcanic rocks of the Anderson-Coyote Reservoir area lie within the Santa Clara Formation. They consist of pyroclastic rocks and olivine basalt flows which are concentrated in four areas within the zone of the Calaveras, Silver Creek, and Coyote Creek faults. These four areas represent the remnants of once more extensive deposits as indicated by small isolated volcanic outcrops found throughout the area. Although the rocks represent the same general volcanic episode, each of the four major ares of outcrop will be described separately. This will be followed by sections on stratigraphy, petrography, chemistry, ultramafic inclusions, and a brief discussion of the geologic history of the volcanic sequence.

DISTRIBUTION.--Prominent exposures of the volcanic rocks within the Santa Clara Formation are located west of Anderson Reservoir area (I), adjacent to both Anderson Reservoir and Coyote Creek area (II), south of Coyote Lake area (III), and north of San Felipe Lake area (IV) (fig. 5) over a distance of about 26 km.

Anderson Dam Area (I).--The northernmost exposure of volcanic rocks lies on an upfaulted block approximately 1.5 km west of Anderson Dam. It is bounded on the west by the Coyote Creek Fault and on the east by the Silver Creek Fault (plate 1). Here the volcanic rocks rest conformably on the Santa Clara Gravels, which in turn rest unconformably on serpentinite. The volcanic rocks cover about a square kilometer of area, and may reach a thickness of 350 meters.

The tuffaceous rocks form an oval outcrop pattern along the perimeter of area (I). They dip at moderate to steep angles toward the center of the area forming a saucer-shaped deposit. Of the three basaltic outcrops pictured in figure 6, one has columnar joints protruding from the central portion and

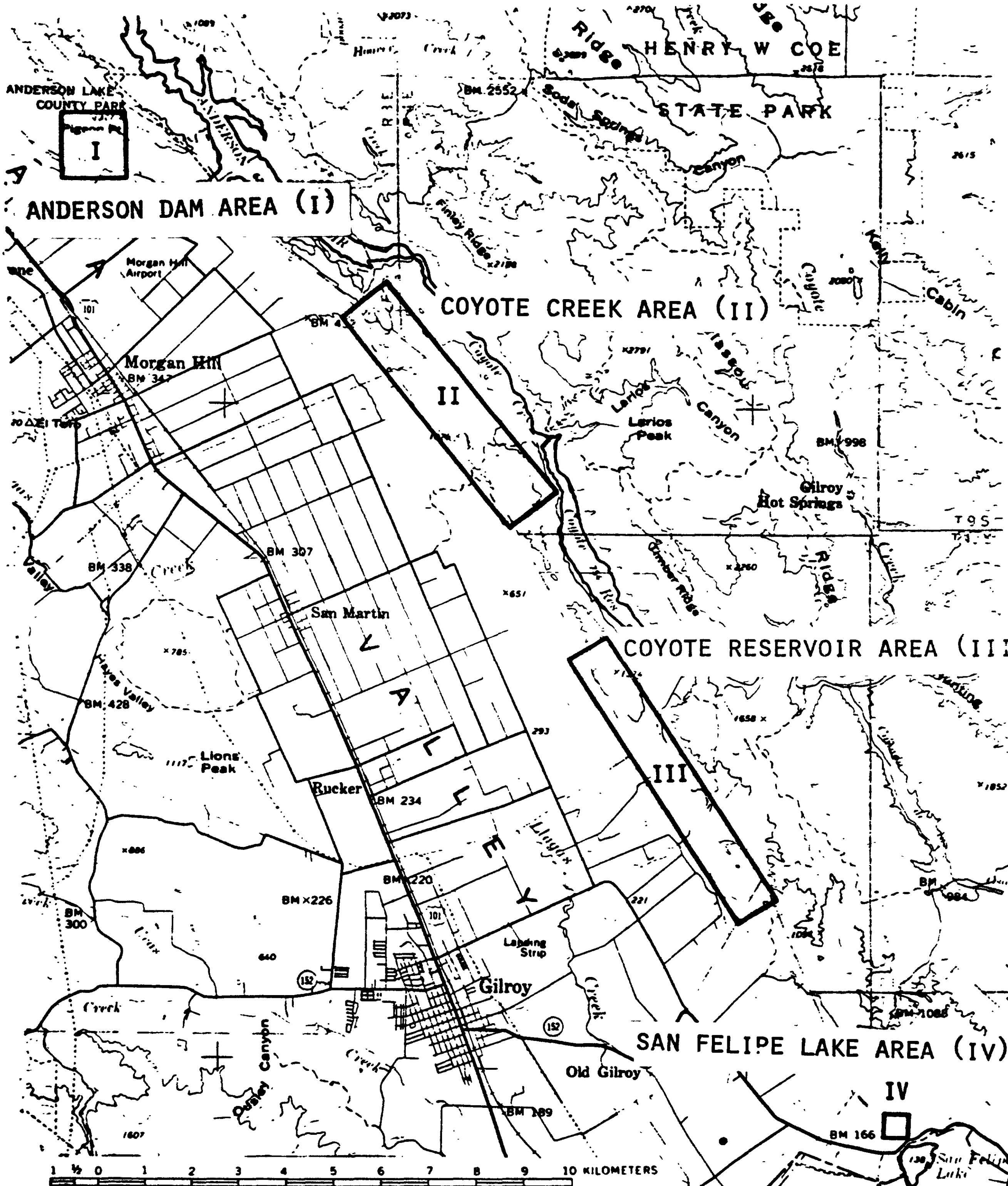


Fig. 5.--Map showing the distribution of the volcanic rocks; (I) Anderson Dam area, (II) Coyote Creek area, (III) Coyote Reservoir area, and (IV) San Felipe Lake.

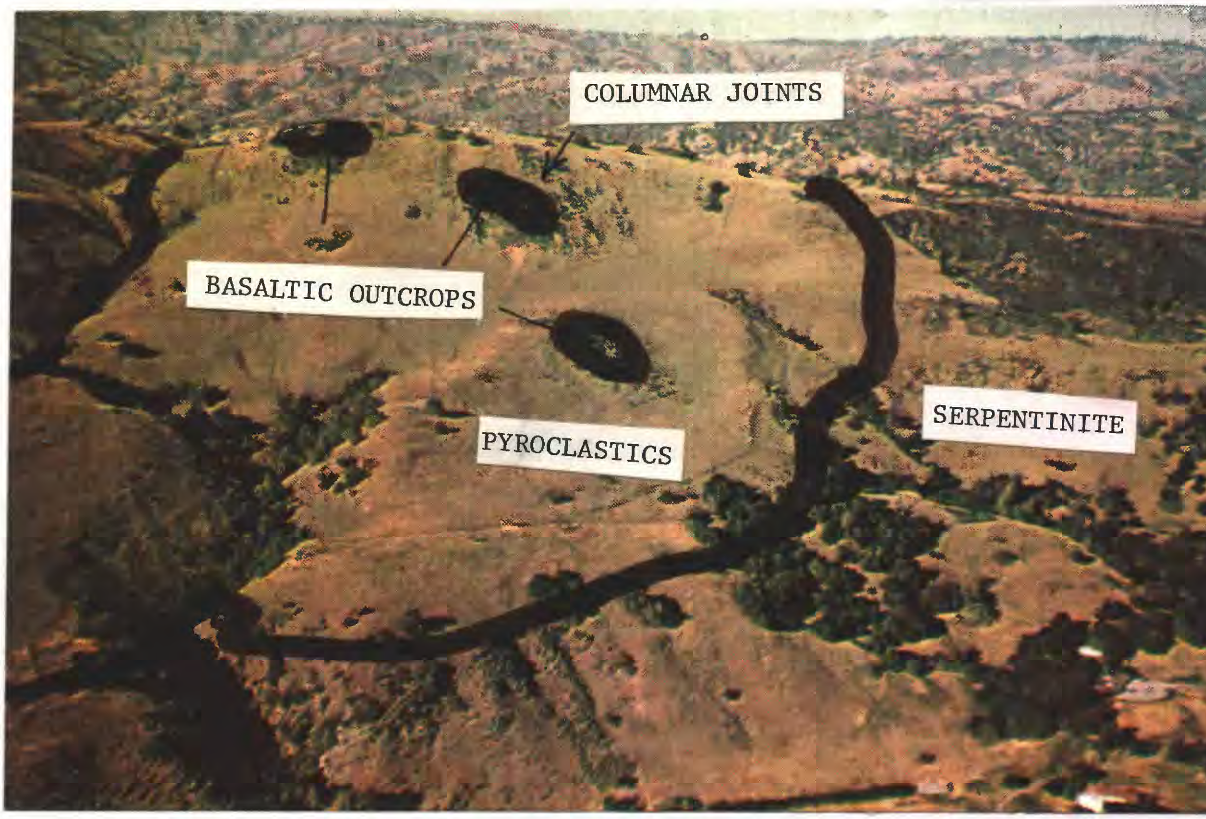


Fig. 6.--Aerial view of the Anderson Dam area (I), showing the disribution of basaltic outcrops. View is towards the northeast.

covers 150 to 200 square meters. This outcrop is surrounding by a massive breccia which exhibits no bedding features. The jointed columns are 40 to 80 cm in circumference, commonly 10 to 20 m long, and are oriented perpendicular to the hillside. Although this orientation is typical of basalt flows, it is also consistent with a venting area as illustrated in figure 7. During the waning stages of volcanism, the lava cooled forming columnar joints perpendicular to the underlying rocks and the air-lava interface (fig. 7A). Since the basalt usually is more resistant to erosion than the surrounding rock, what remains today is a circular outcrop of basalt with columnar joints that is surrounded by massive breccia (fig. 7B). This rock association of basalt and breccia, and the lack of tuffs suggest that this area probably served as a vent for the tephra and subsequent lava flows (MacDonald, 1972).

Coyote Creek area (II).--This volcanic sequence unconformably overlies serpentinite, Franciscan, and Great Valley rocks. However, it is in conformable and partial fault contact with the Plio-Pleistocene Santa Clara Gravels. It is bounded to the west by the Coyote Creek Fault and to the east by the Calaveras Fault. The Franciscan assemblage and the serpentinite exposed to the southeast of the cross fault seem to be differentially uplifted as only small remnants of the volcanic rocks remain south of the fault (cross section 5-5', plate 1). The entire volcanic sequence at this locality has been deformed into folds with axes trending northwest-southeast.

Adjacent to the Coyote Creek Fault on the new East Dunne Avenue, an olivine basalt flow is interbedded with the Santa Clara Formation (fig. 8 and cross section 3-3'). The flow is over 15 m thick, but thins to the southeast. At the contact with the gravels, a baked zone approximately 40 cm thick stands out conspicuously indicating that the flow is overturned. Below this zone of oxidation the flow becomes quite massive and grades into a highly

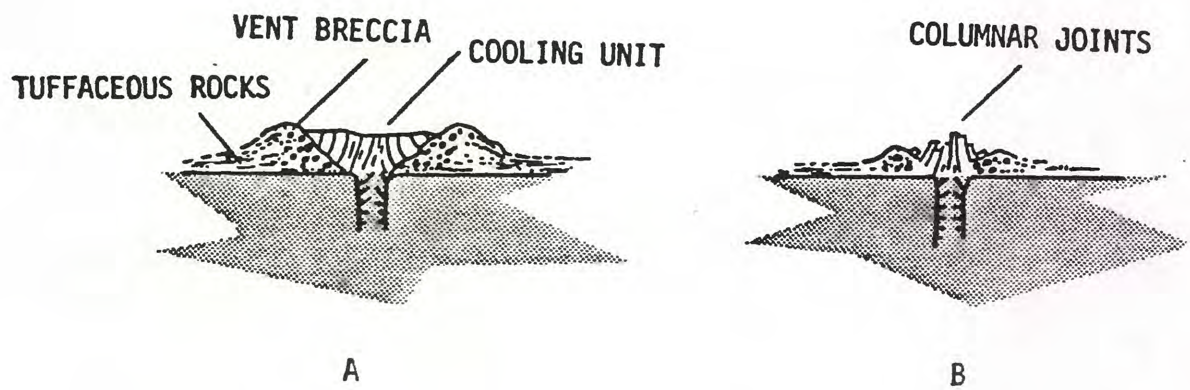


Fig. 7.--Idealized drawing of vent area, modified after Williams (1936) (A) During the last stages of volcanism, joints form perpendicular to the cooling surfaces. (B) Erosion strips most of the surrounding rock leaving remnants of the breccia and columnar joints perpendicular to the ground surface.

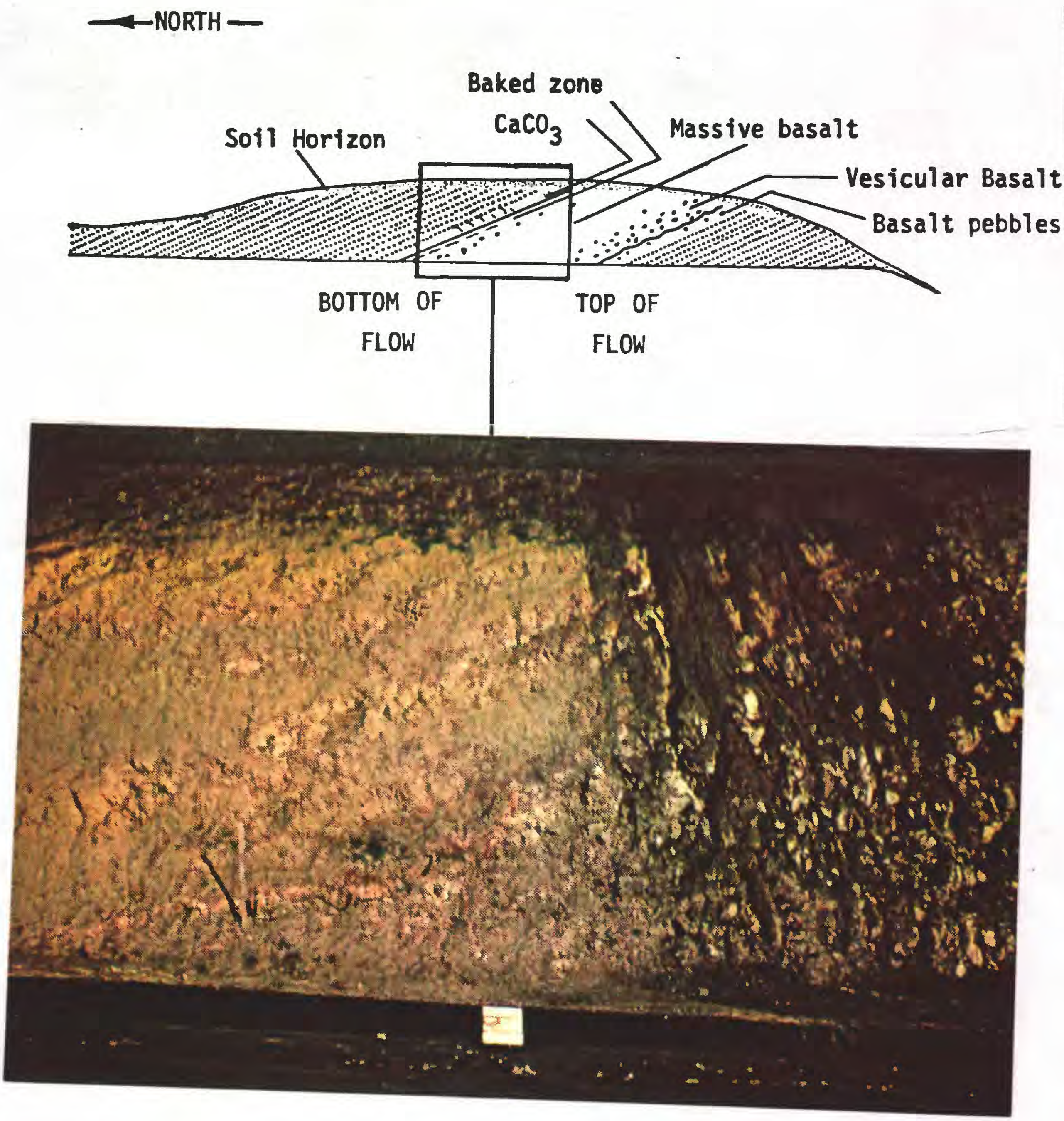


Fig. 8.--Overturned basalt flow interbedded with the Santa Clara Formation located on East Dunne Avenua, 1.4 km from the valley intersection of Thomas Drive and East Dunne Avenue.

vesicular zone at the original top of the flow. Along the upper contact, small rounded pebbles of basalt are found in the base of the overlying sediments.

Coyote Lake Area (III).--The Coyote Lake volcanic rocks lie south and southeast of Coyote Reservoir. It is bounded on the west by the Coyote Creek Fault and on the east by the Calaveras Fault. This unit rests conformably on gravels of the Santa Clara Formation, but also unconformably overlies the Knoxville Formation, Franciscan assemblage, and serpentinite.

Although no circumferential glass selvage, stretched vesicles or aligned plagioclase laths were recognized at the interface between the basalt and country rock, other lines of evidence suggest that this area may have acted as one of the volcanic vents for the Anderson-Coyote Reservoir area. They are as follows: (1) the basaltic outcrop is nearly circular in ground plan, typical of many plugs (MacDonald, 1972), (2) according to MacDonald (1972), those vents and plugs underlain by basalt are more resistant to erosion than the enclosing rock and form areas of bold relief as illustrated in figure 9. (3) those basaltic samples recovered from the top of the hill (fig. 9) are quite vesicular while those recovered from the basal exposure and the drill core (16.3 m) are quite massive suggesting that the top of the hill was once close to the surface consistent with a vent area, and (4) drill cores 1, 2, 3, and 4 (fig. 12) cut only basalt and breccia with no evidence of tuffaceous rocks, a rock association typical of vent areas.

San Felipe Lake Area (IV).--This area, located 400 m north of San Felipe Lake and directly east of the active trace of the Calaveras Fault, covers an area of less than .23 square kilometers. It either unconformably overlies or

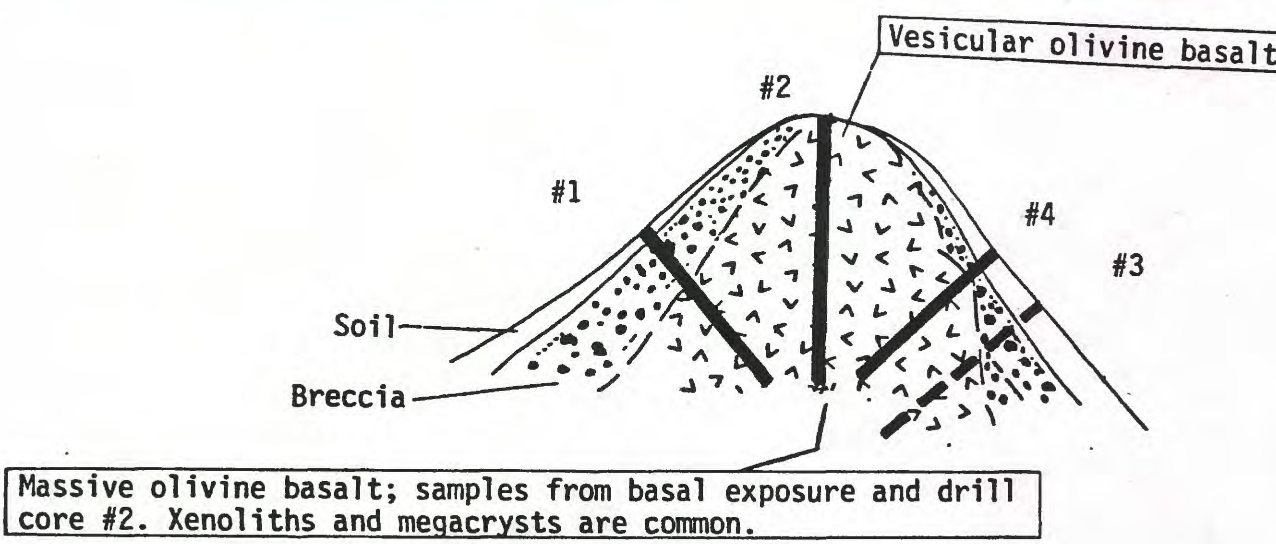


Fig. 9.--A prominent circular shaped hill adjacent to Coyote Lake is underlain by basalt and breccia. The view is toward the southeast. (INSET) A diagrammatic cross section of the vent area showing the breccia/basalt rock association and drill core orientation. Drill core locations are plotted on the Gilroy 7.5' quadrangle (fig. 10).

cuts serpentinite, but the contact relationship remains unclear. The isolated nature of the exposure suggests that this outcrop may represent a portion of the volcanic sequence offset in the Calaveras Fault zone. It is the only recognized volcanic rock exposed east of the active trace of the fault, and possibly indicates minimum right lateral displacement of 5 km.

The exposure consists of large blocks of massive olivine basalt apparently resting on serpentinized ultramafic rock. Flow structures are found locally, but the random orientation of the blocks makes reconstruction of a flow direction impossible. No pyroclastic rocks were found at this locality.

STRATIGRAPHY.--Five lithologic units will be described in ascending stratigrraphic order. They are: [1] transitional rocks, [2] tuffaceous rocks and lapilli agglomerate (QTv_3), [3] baked tuffaceous contact, [4] flow and air-fall breccia, agglomerate (QTv_2), and basalt (QTv_1). However, because of the small map scale only three of these units [2], [4], and [5], are shown on the geologic map (plate 1). This lithologic series represents the general chronological sequence of events in the Anderson-Coyote Reservoir volcanic pile established by mapping. However, this stratigraphy must be applied carefully in areas where the entire section is not exposed because basalt flows and pyroclastic horizons alternate in widely varying proportions, as indicated by drill core logs (fig. 11 and 12) supplied by the Granite Rock Company of Watsonville, California. A cross-section that was constructed using cores 5 through 10 (fig. 11) shows that the rapid lateral variation and interfingering of the volcanic rocks precludes the construction of a typical measured stratigraphic column which would describe the entire Anderson-Coyote Reservoir volcanic section. In addition, representatives of each rock type are not always present at all major exposures. Consequently, the stratigraphic column (fig. 13) is an idealized one.

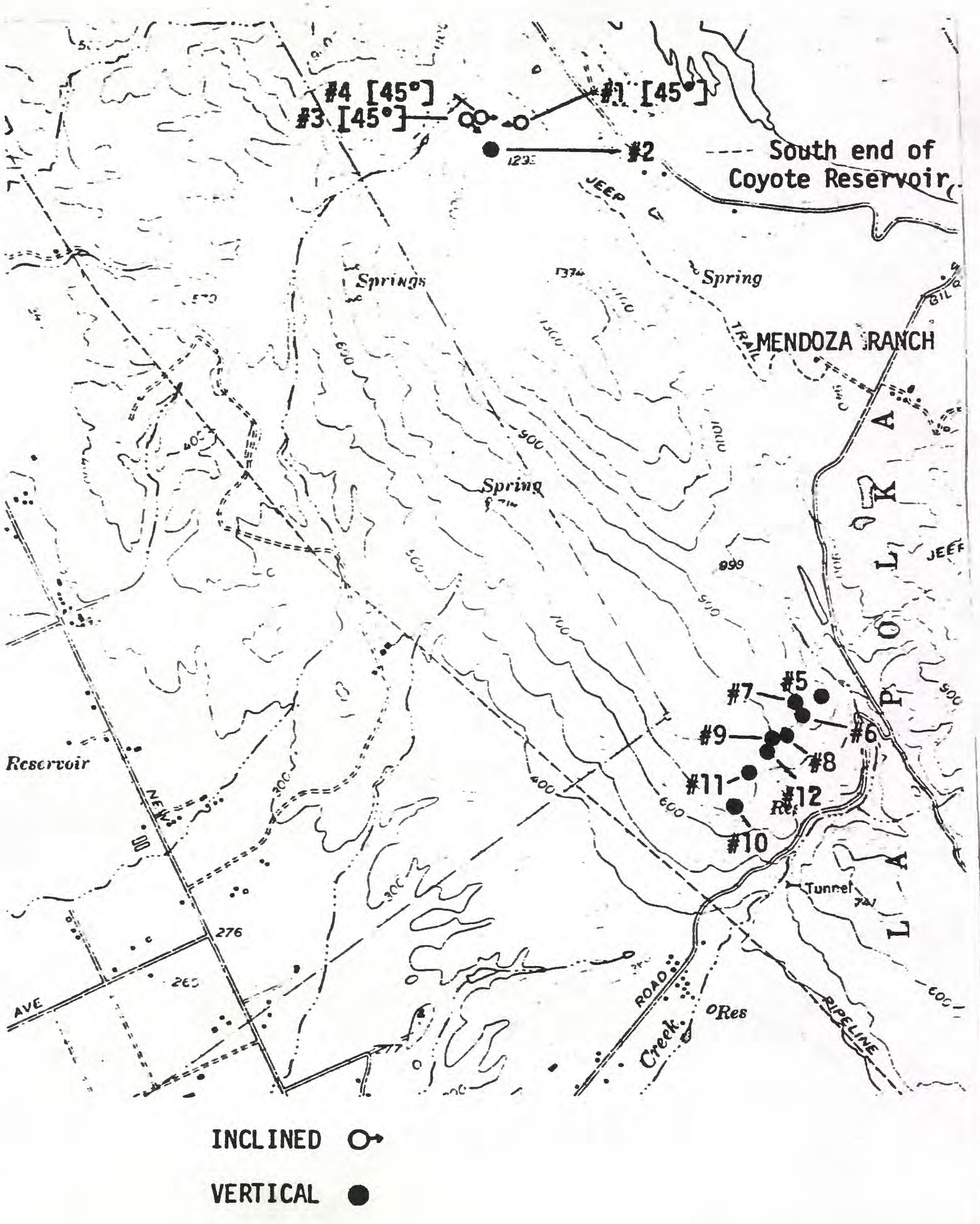


Fig. 10.--Drill core localities plotted on the Gilroy 7.5 minute quadrangle.

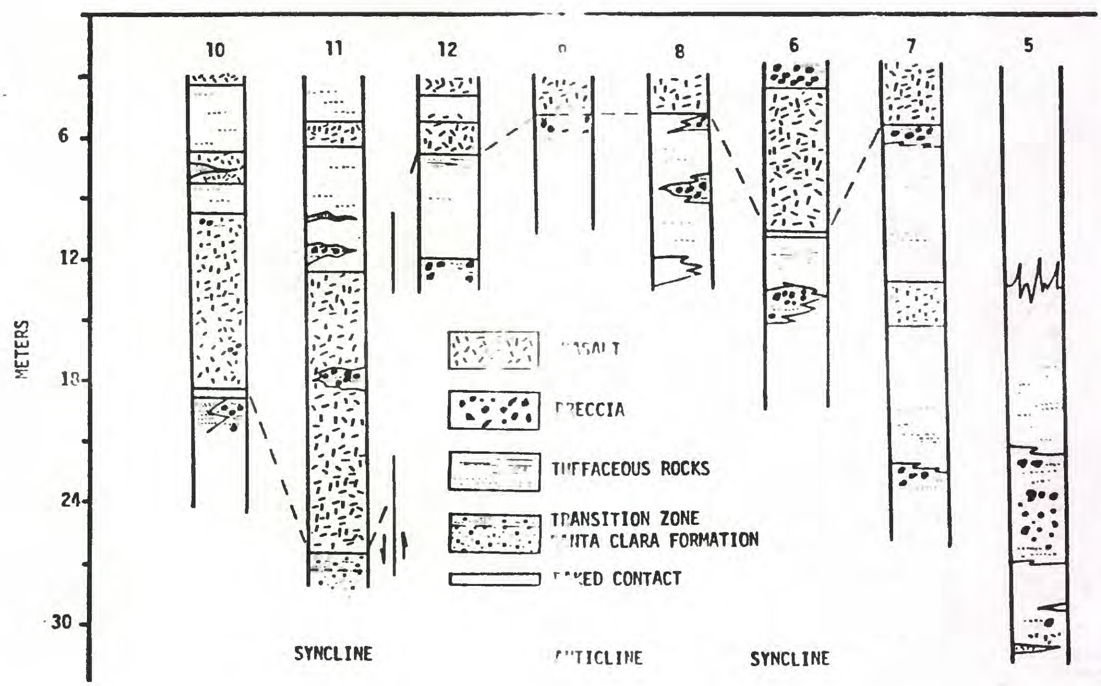


Fig. 11.--Cores 5, 7, 8, 9, 12, 11, and 10 are perpendicular to the major structural trend of the Coyote Reservoir area (III) and helped delineate a folded structure which is structurally consistent with attitudes taken on the surface.

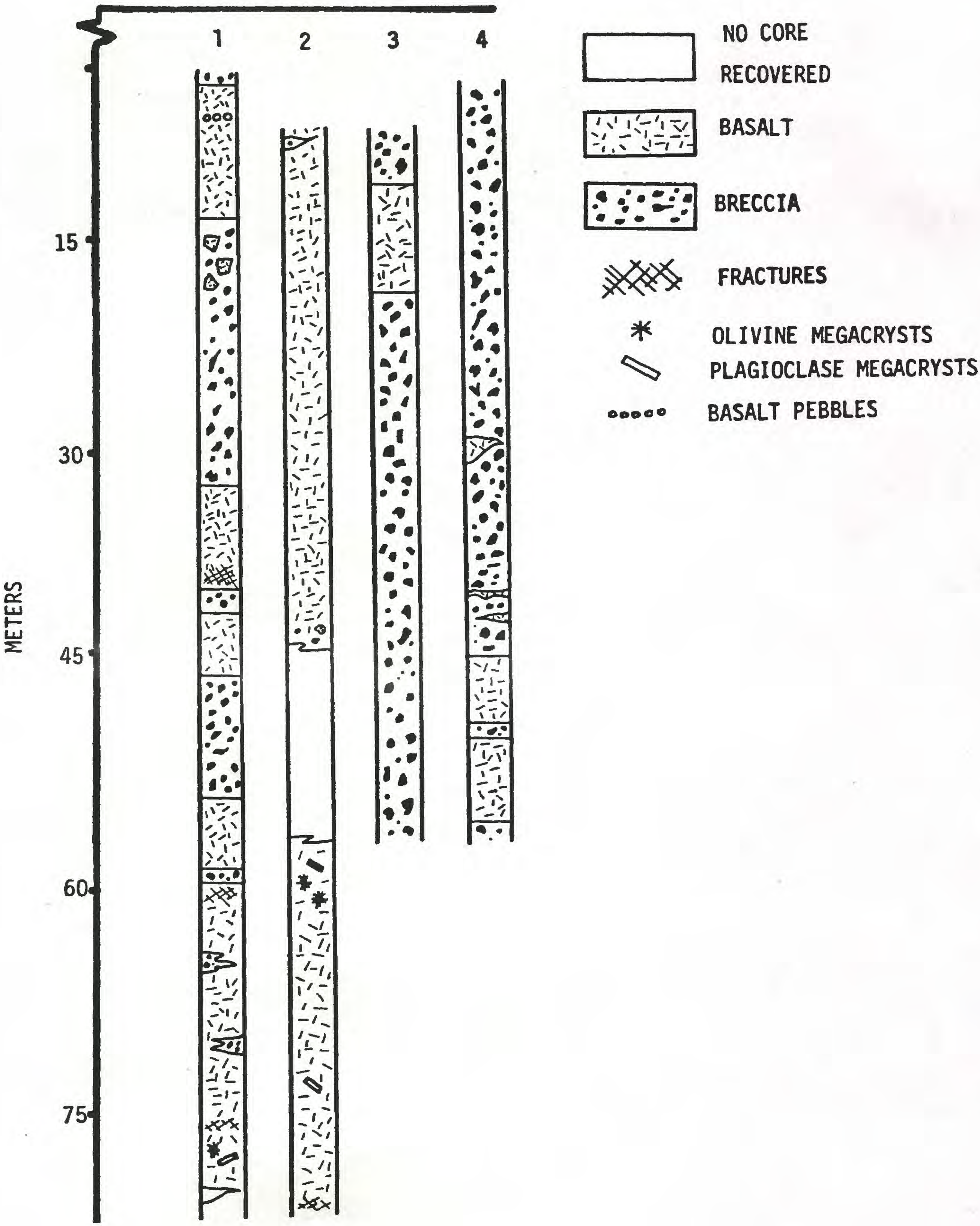
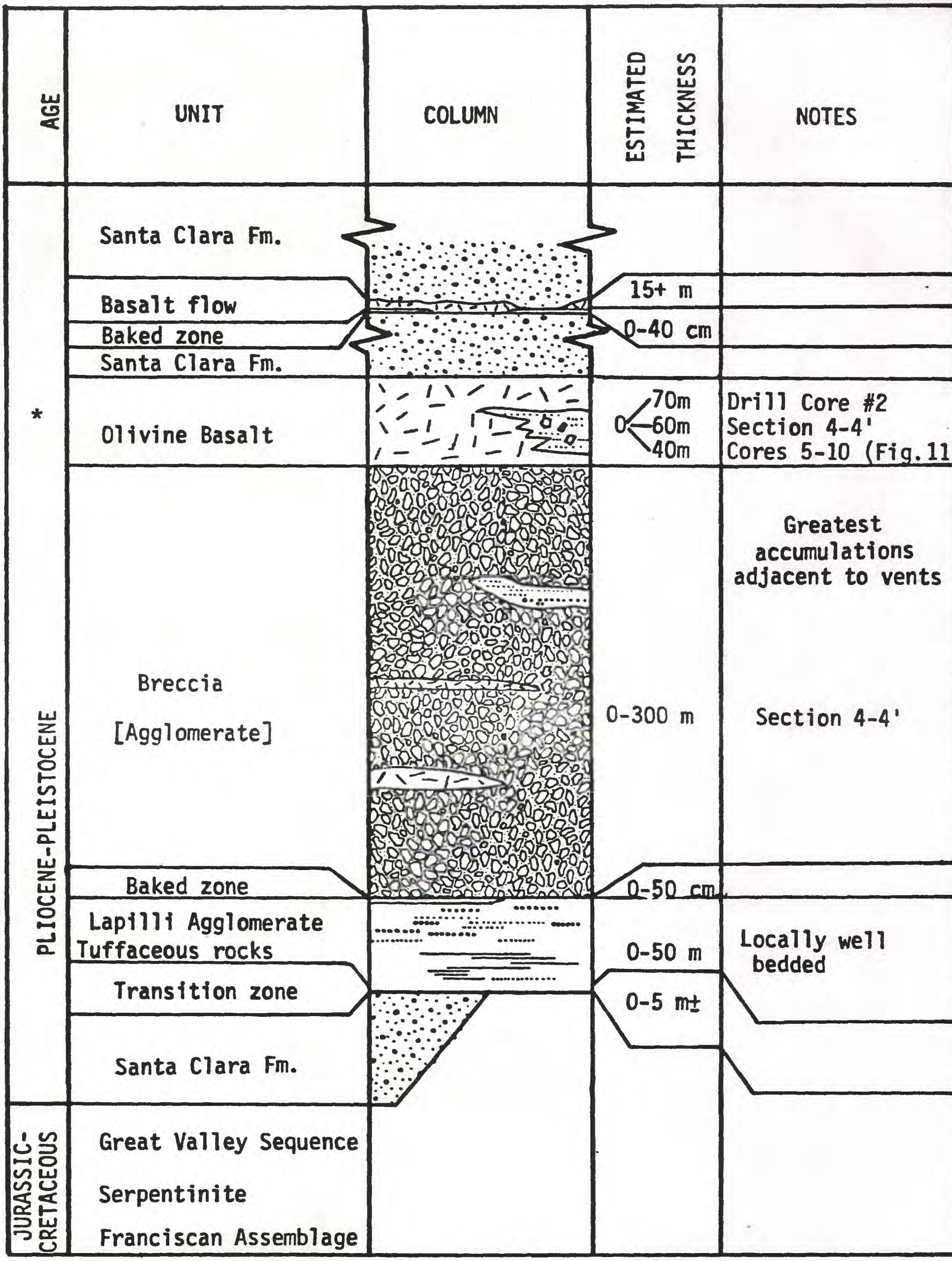


Fig. 12.--Lithologic logs from cores 1, 2, 3, and 4. Core #2 represents a vertical section through the basaltic plug. Drill cores 1, 3, and 4 cut mainly breccia and olivine basalt and lack tuffaceous material.



*K/Ar date, Sarna-Wojcicki, U.S. Geological Survey, 3.5 m.y.

Fig. 13.--Idealized stratigraphic column of the Anderson-Coyote Reservoir volcanic rocks. The description of rock units is presented on plate 1.

Transitional rocks.--The pyroclastic rocks are separated from the Santa Clara gravels, serpentinite, Knoxville Formation, and Franciscan assemblage by a zone of transitional rocks, which are not uniform in distribution, thickness, or lithology. Within this gradational zone, the Santa Clara gravels become progressively richer in volcanic ash, which acts asa cementing agent for the loosely consolidated sediments (fig. 14). The best example of this consolidated zone is exposed at the western margin of area (I), where it maintains an abnormally high slope for the Santa Clara gravels, but, even there lack of good exposures prevents an estimation of thickness. Since the volcanic rocks were deposited concurrently with the deposition of the Santa Clara gravels, there may be more than one Santa Clara gravel-pyroclastic rock transition zone.

Where the volcanic rocks unconformably overlie serpentinite, Knoxville Formation, or the Franciscan assemblage, small pebbles from these units are found within the transitional zone. This zone is quite massive and bedding features were not recognized. Sorting is poor with rocks from the undelying units up to 50 cm in diameter incorporated within the transitional zone. Although total thicknesses could not be determined because of poor exposures zones from 1 to 5 m were measured, and these represent minimum thicknesses. Colors of the transition zone above the Knoxville formation and Franciscan assemblage typically range from tan to an orange-brown, but greenish-gray zones are found overlying serpentinite. Along the southern serpentinite transition zone, in the Anderson Dam area (I), pale-green to gray clasts of altered serpentinite are found within a matrix of lapilli agglomerate and tuffaceous rocks. These clasts may have formed as a result of the reaction between hydrous serpentinite and the ascending volcanic rock. Whole-rock X-ray analysis shows that the sample consists of orthopyroxene (enstatite-

Fig. 14.--Transition zone between the Santa Clara gravels and the tuffaceous rocks located in the Anderson Dam area (I) adjacent to the Coyote Creek Fault. Here a tuffaceous matrix acts as a cementing agent binding the pebbles together. Field of view 35 x 25 cm.

hypesthene). A possible explanation for the apparent transformation of serpentine to orthopyroxene is as follows. The initial peridotite, possibly harzburgite, was hydrated to form serpentinite. This rock was then dehydrated by the ascending volcanic rocks and recrystallized to form orthopyroxene and olivine(?), subsequent weathering producing the end products of residual orthopyroxene.

Tuffaceous rocks and lapilli agglomerate.--The lapilli agglomerates and tuffs are restricted to the perimeter of the Anderson Dam area (I) and attain a thickness of approximately 80 m. In the Coyote Creek area (II) and Coyote Reservoir area (III), similar folded pyroclastic rocks range in thickness from 3 to 100 m and trend parallel to the Santa Clara Valley. They are well-bedded, but become massive and locally exhibit graded bedding (fig. 15). Often the agglomerate and tuff beds alternate with thicknesses varying from 1 mm to over 5 cm. Locally, the loosely consolidated lapilli differentially weather leaving the more resistant tuff beds extending beyond the agglomerate (fig. 16). Associated with the volcanic debris are varying amounts of quartz, feldspar, and lithic fragments that are not of volcanic origin. These clasts are angular to well-rounded and range from 1 mm to over 30 cm in diameter. Small carbonized wood fragments occur less abundantly along bedding planes and often appear as brownish-black residues. The existence of organic material suggests that deposition may have occurred in a lacustrine environment, but definite indicators such as macro- or microfossils were not found.

Generally, the pyroclastic rocks are poorly consolidated and maintain low to moderate slopes. In those areas where exposures are absent, soil color helped differentiate rock types. Soils derived from the tuffaceous rock are typically light brown and contrast well with the darker-brown basaltic soils. Relatively fresh exposures are all shades of brown, but become lighter

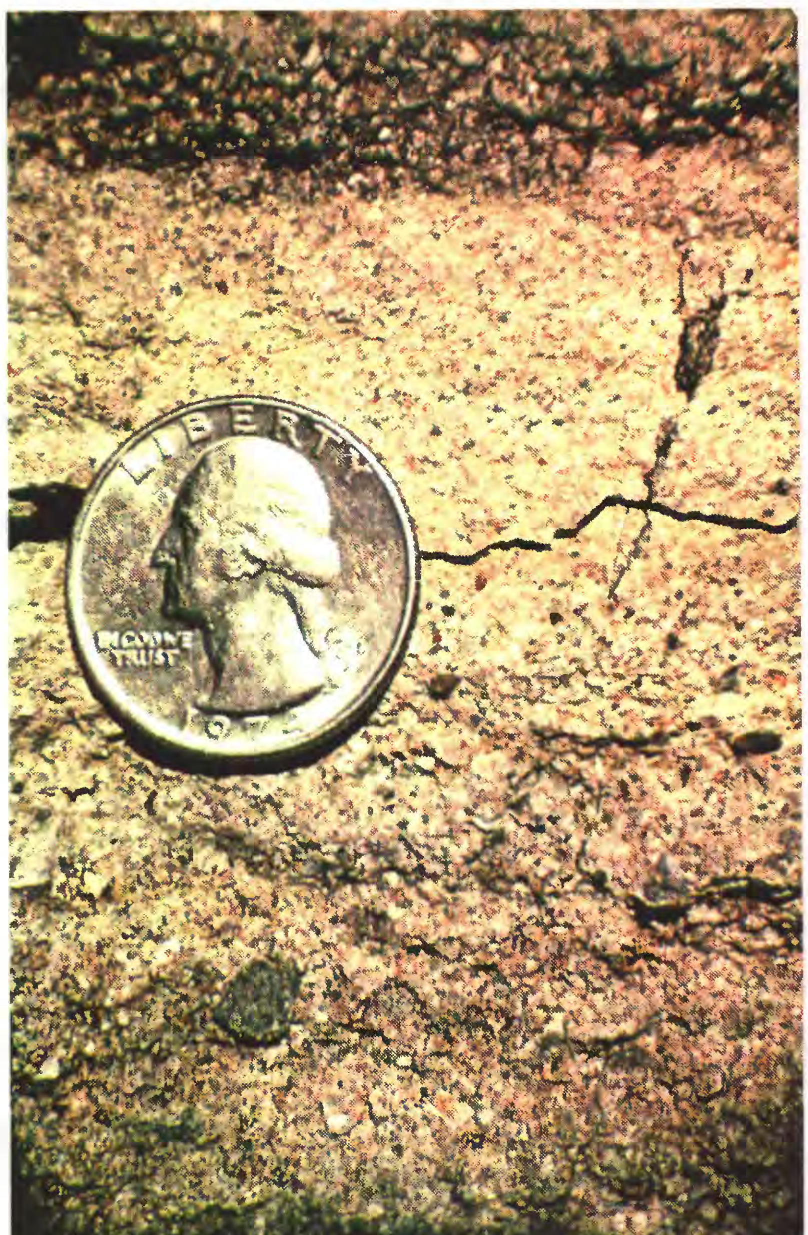


Fig. 15.--Tuff showing graded bedding, located .25 km west of Coyote Dam.

Fig. 16.--Outcrop of tuffaceous rocks and interbeds of lapilli agglomerate exposed in the Anderson Dam area (I) near the northwestern serpentinite contact.

as weathering progresses. At the Anderson Dam area (I), some beds have a distinctive bluish cast similar to the blue nontronite-bearing Neroly and Merhten Formations, but the material was not X-rayed to confirm this similarity.

Baked contact.--The reddish-orange zone of oxidation reaches a thickness of about 50 cm, but it was only locally recognized (fig. 17). The best examples are found in the Anderson Dam area (I) where the breccia baked the tuffaceous rock (fig. 18) and drill cores 6 and 10 (fig. 11) where basalts welded the tephra and other clastic fragments. The tephra and other pebbles have been partly welded in this zone making outcrops quite resistant. In addition, the absence of deformation along the contact indicates that the tuffs and lapilli agglomerates were probably well lithified or covered by water prior to the deposition of the breccia. The limited occurrence of this baked contact may be accounted for by (1) poor exposures, (2) the restricted areal extent of the breccia or basalt, and (3) deposition occurring in water, which prevented baking.

Breccia (agglomerate).--Both flow breccias (autobrecciated lava flows) and air-fall breccias are found within this area; however, the latter rock type is the more common. Typically the flow breccias consist of slightly vesicular to scoriaceous blocks of basalt up to 1 m in diameter. The air-fall breccias on the other hand consist of fragments less than 50 cm in diameter which are often interbedded with tuffs and lapilli agglomerate. It is often difficult to distinguish the difference as surfaces of scoriaceous blocks in the flow breccias weather and form what appears to be a tuffaceous matrix. Relatively fresh surfaces are gray to off-white, but often weather to darker colors (fig. 19).

Fig. 17.--Closeup of a relatively fresh exposure of the baked zone showing the tuffaceous matrix partially annealed and oxidized helping to bind the volcanic fragments together.

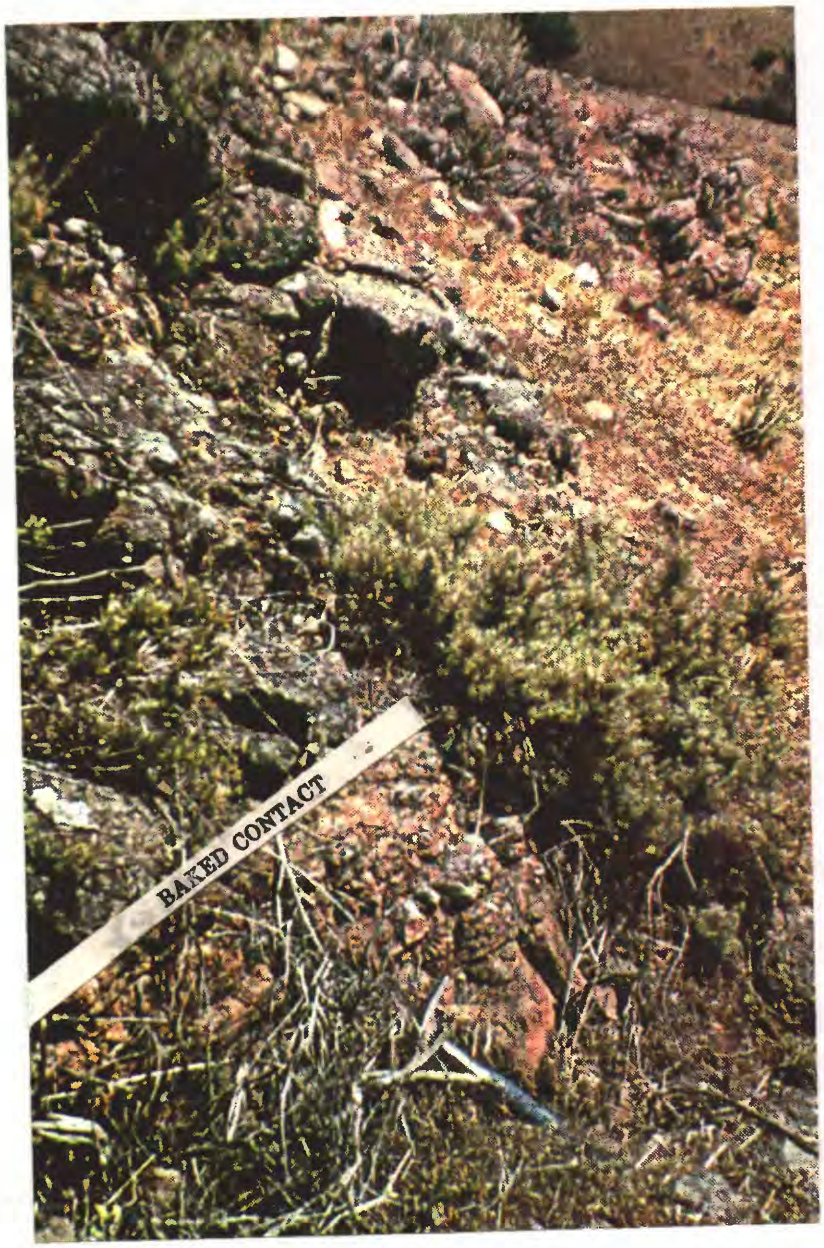


Fig. 18.--Tuffaceous rocks baked by the flow breccia, Anderson Dam area (I).

Fig. 19.--Typical exposure of breccia (air fall) in the Coyote Creek area (II), located 1.3 km southwest of Mud Lake.

Unlike the flow breccias which are low in lapilli, the air-fall breccia unit contains up to 40 percent of lapilli size fragments which vary in concentration both laterally and vertically. Most of these fragments vary from slightly vesicular to scoriaceous and are easily broken. However, massive basaltic blocks (greater than 60 cm in diameter) are often found incorporated in both breccias. In addition, andesitic clasts are occasionally found in the breccias and may be related to the andesite found in the Silver Creek area (T. H. Rogers, oral commun., 1973). The matrix of both breccias consists of ash and fine-grained equivalents of the larger fragments.

Olivine basalt.--The olivine basalt occurs predominantly as randomly oriented blocks in surface float (fig. 20). Distinct flows could not be delineated because of poor exposures. Fresh surfaces are bluish-black, but weather to colors ranging from light-brown to off-white. The flows were probably erupted from a sequence of vents and fissures controlled by the Calaveras Fault system as suggested by their subparallel position along the fault zone. The basaltic plugs are generally massive, but become quite vesicular in those shallow areas that were close to the surface at the time of eruption. Many of the cavities are now filled with secondary minerals, which will be described in a later section.

Three varieties of basaltic float commonly are found: (1) massive, (2) vesicular, and (3) one with a peculiar grape-like appearance on weathered surfaces. Several of these grape-like structures were slabbed through to unweathered surfaces and inspected for macrostructures and compositional differences. However, there were no visible fractures or apparent compositional differences to explain these features. In addition, spheroidally weathered basaltic blocks are found locally (fig. 21).

Fig. 20.--Typical exposure of randomly oriented basaltic float, located 1.5 km southwest of Coyote Dam.

Fig. 21.--spheroidally weathered basalt found in the Coyote Creek area (III).

Xenoliths of spinel peridotite are found throughout the area, but they are most abundant at two localities: (1) a vent adjacent to Coyote Reservoir (GI-1), and (2) as float of a basalt flow 3.2 km north of locality (GI-2) adjacent to Coyote Reservoir. These areas are diagrammatically indicated on the geologic map with the symbol .

PETROGRAPHY

Pyroclastic rocks.--The pyroclastic deposits are subdivided into three categories on the basis of clast size. These rocks may be further classified on the basis of their content of lithic fragments, glass, and crystals. Using these constituents, a variety of rock names may be derived when used in conjunction with the size classificatin. The rocks are listed below in decreasing order of abundance. However, statistical methods were not used in determining these percentages.

Compositional Classification	Compositional + Size Classification	Pore Space	Vol. % rocks in thesis area
Lithic	Lithic Tuff Lithic Lapilli-Tuff Lithic Lapilli-agglomerate		90%
Vitric (glass)	Vitric Tuff Vitric Lapilli-Tuff Vitric Lapilli-agglomerate	0-25%	10%
Crystal	Crystal Tuff Crystal Lapilli-Tuff		?
Combinations of the above	i.e. - Lithic Vitric Tuff		

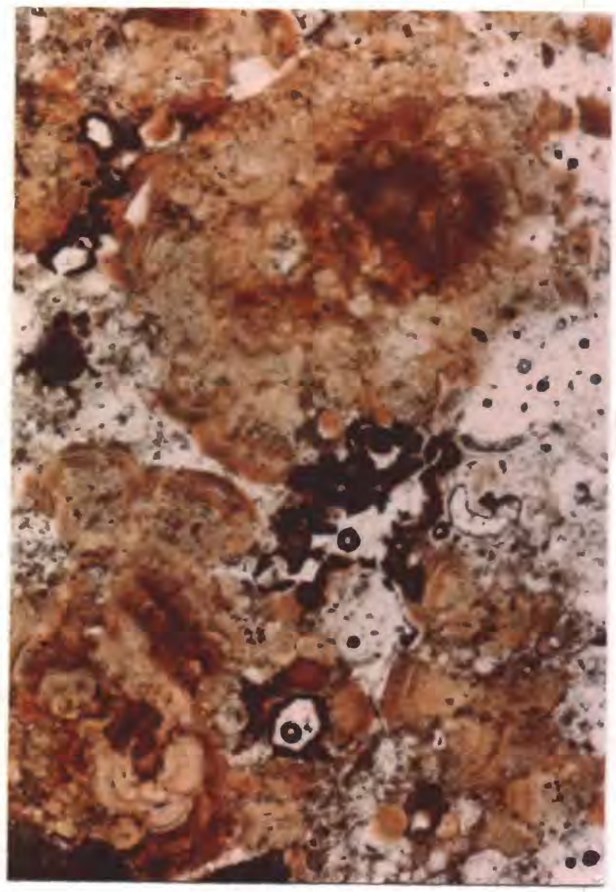
Virtually all the pyroclastic rocks are weathered to some degree, even those recovered from drill cores. Consequently, the colors observed may not represent fresh colors. However, relatively fresh samples range in color from brownish-gray to cream and often weather to lighter hues. Porosity was determined by visual inspection of thin-sections using 10 x magnification and a 1 mm grid. The range 0-25 percent are maximum values as weathering and thin section preparation increased porosity.

Lithic Tuff.--Lithic tuffs predominantly consist of porphyritic basalt clasts which range from 0.5 to over 4 mm in diameter. These basalt clasts contain phenocrysts of plagioclase, olivine (often altered to iddingsite), and augite. They are typically angular to subrounded, but occasionally well-rounded ones are found. Somewhat less common are subrounded fragments of aphyric basalt, serpentinite, graywacke, chert, gabbro, and actinolite schist. The fragments are set in a matrix of pale brown glass locally exhibiting spherulitic texture, small microlites (less than 12 microns in diameter) and clay, which make up 20 to 30 percent of the sample. Locally, the mafic glass has altered to palagonite and ranges in color from amber yellow to a reddish brown in plane polarized light. It is usually concentrically banded (fig. 22), but oolitic forms are common in cavities in vesicular basalt fragments. Palagonite often acts as a cementing agent with calcite and is responsible for imparting strength to outcrops. The presence of palagonite, calcite (GI-5, 8), high concentrations of mercury (GI-4, 5, 9) (see table 3, page 77) and clay suggest that circulating waters played an important part in the chemical and physical characteristics of the tuffs.

Sorting is moderate to poor in most tuffs, but improves in the graded beds. In these beds the glass matrix (less than 6 microns) and small crystals (13 microns to 100 microns) of plagioclase are concentrated at the top while the larger lithic fragments, plagioclase, and mafic minerals (up to .25 mm in diameter) increase toward the bottom (fig. 23).

Vitric Tuff.--Devitrified glass is the most abundant constituent in the matrix of the vitric tuffs. Locally it has partly altered to palagonite

Plane-polarized light



1 mm

Fig. 22.--Amber yellow to reddish brown palagonite in plane polarized light. The concentric nature is due to palagonite forming around glass fragments or other nucleii.

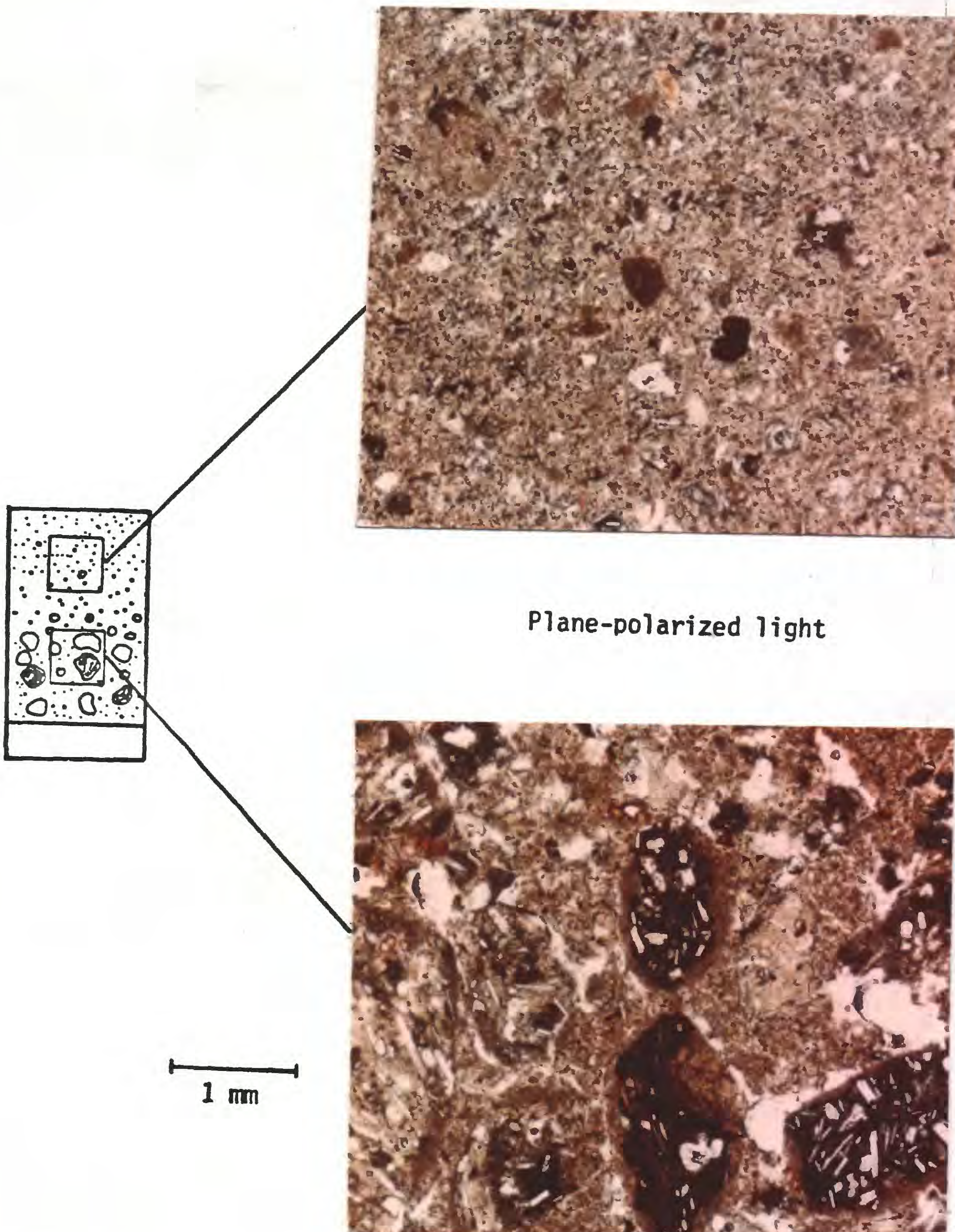


Fig. 23.--Photomicrograph of graded tuff showing the upper horizon which consists of ash, small crystals and minute basaltic fragments while the lower horizon consists of basically the same material with the addition of larger fragments of porphyritic basalt.

and a chloritic substance which appears greenish-yellow to a yellow-brown in plane polarized light. Much of the yellowish material has refractive indices below 1.54 indicating palagonite. Reconstruction of the original percentages of glass prior to alteration shows that glass ranged between 5 and 50 percent and averaged approximately 30 percent of the rock. The remainder of the matrix consists of small lithic fragments and crystals of plagioclase and olivine (60 to 400 microns in diameter). Varying amounts of lithic fragments (0.5 to 1.5 mm in diameter), crystals of plagioclase, and olivine (0.1 to 1.5 mm in diameter) form the remainder of the rock.

Crystal Tuff.--Crystals typically comprise between 1 and 10 percent of the pyroclastic rocks, but increase to 30 percent in the crystal tuffs. Plagioclase is the most common crystal and occurs in subhedral to euhedral laths that range from 0.1 to 1.5 mm long. The large laths range from An_{50-70} (labradorite) and smaller ones from An_{30-50} (andesine). Augite is the next most abundant crystal ($2V_z$ approximately 60^o) while olivine occurs less frequently as subhedral to anhedral crystals, commonly surrounded by a rim of iddingsite and/or hematite. These mafic minerals range from 0.5 to 5 mm in length. Magnetite that is partly altered to hematite forms euhedral grains that are not uniformly distributed in the rock. The matrix consists of glass (locally altered) and very small crystals of plagioclase and mafic minerals.

Baked Tuffs.--In some localities, the tuffs have been baked by breccias or basalt flows. The constituents of the tuffs are oxidized to varying shades of red-orange. The mafic minerals commonly are altered to hematite which is translucent red in plane polarized light. Plagioclase and lithic fragments seem to be the least affected, but they are often stained by the red hematite making descriptions of other alteration products difficult.

Breccia.--Breccias are mineralogically similar to the other pyroclastic rocks, and the distinction between coarser lapilli tuffs and the air-fall breccia is somewhat arbitrary. However, in the breccias large blocks of phyric and aphyric olivine basalt are found locally. In addition, fusiform bombs, although uncommon, are locally found in the breccias (fig. 24).

Basalt and Basaltic Andesite.--The artificial boundary between basalt and andesite is not clear. Howell and others (1954) believe that the presence or absence of olivine is not diagnostic, but olivine-rich lavas are more likely to be basalts than andesites. In this study the average normative composition of plagioclase in which Ab is less than An was used to distinguish basalt from basaltic andesite (see table 3B, p. 77). Macroscopically and microscopically the distinguishing characteristics are not entirely clear; consequently, they will be presented together.

Macroscopically, these rocks range from massive to vesicular with the latter variety more common. Microscopically, they are porphyritic to aphyric with macro- and microphenocrysts of olivine, plagioclase, and augite wet in a hypocrystalline groundmass. The groundmass consists of augite, plagioclase, magnetite, glass, and apatite(?). Pehnocrysts comprise 10-25 percent of the rocks. Of the macrophenocrysts, plagioclase ranges in length from 0.75 to 4 mm while olivine occurs primarily as subhedral crystals 0.5 to 2.5 mm in size. Augite forms stubby prismatic crystals 0.5 to 2 mm across. Microphenocrysts of plagioclase, olivine, and augite, which are all smaller than 0.5 mm, are usually set in an intergranular groundmass, but intersertal and trachytic textures also occur. Glomeroporphyritic texture is locally present. Typical examples of these textures are illustrated in figures 25, 26, 27, and 28.

Fig. 24.--Almond-shaped fusiform bombs are common to eruptions with low viscosity lavas. These samples were found as surface float 1.6 km southeast of Coyote Dam.

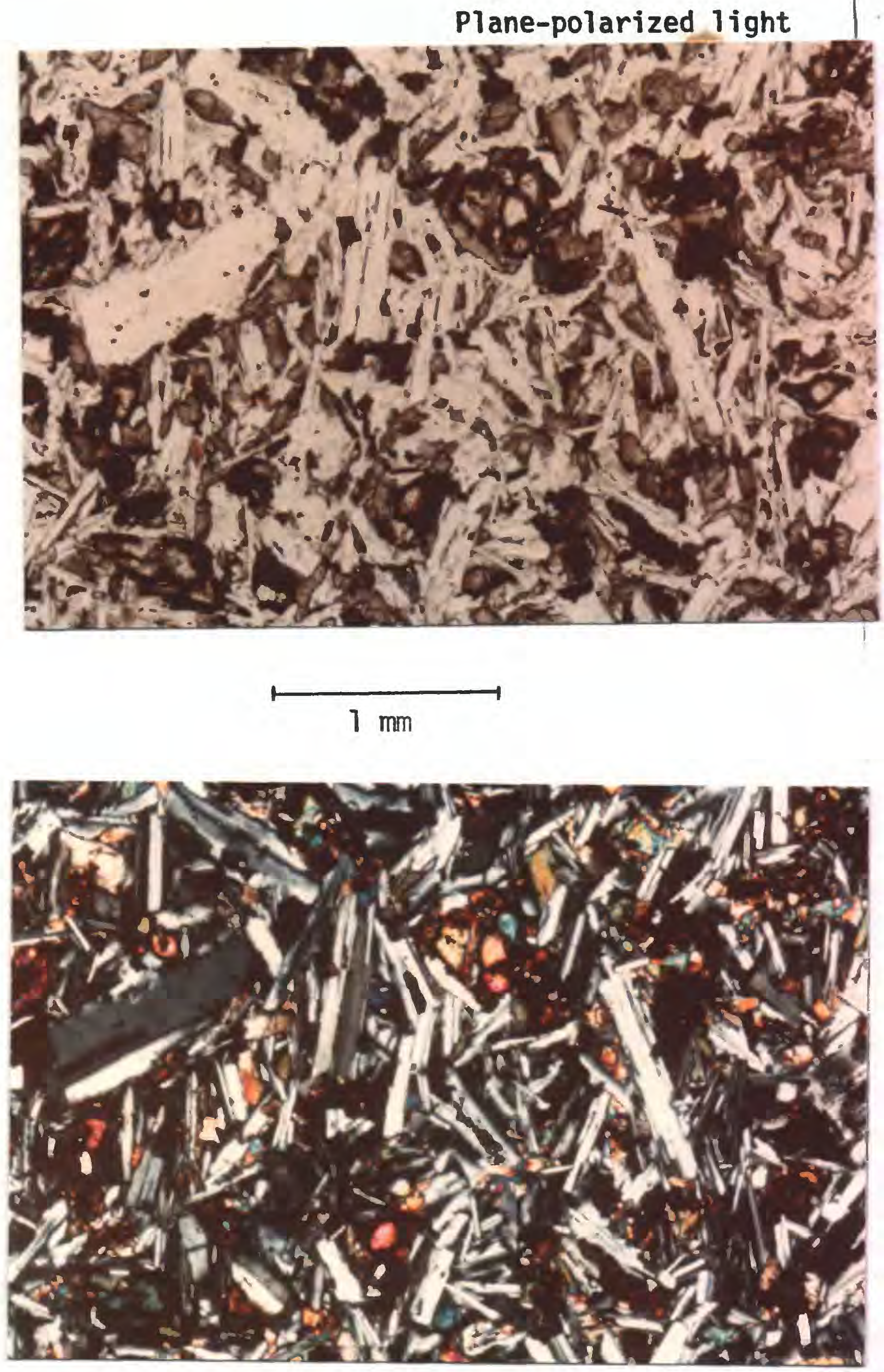
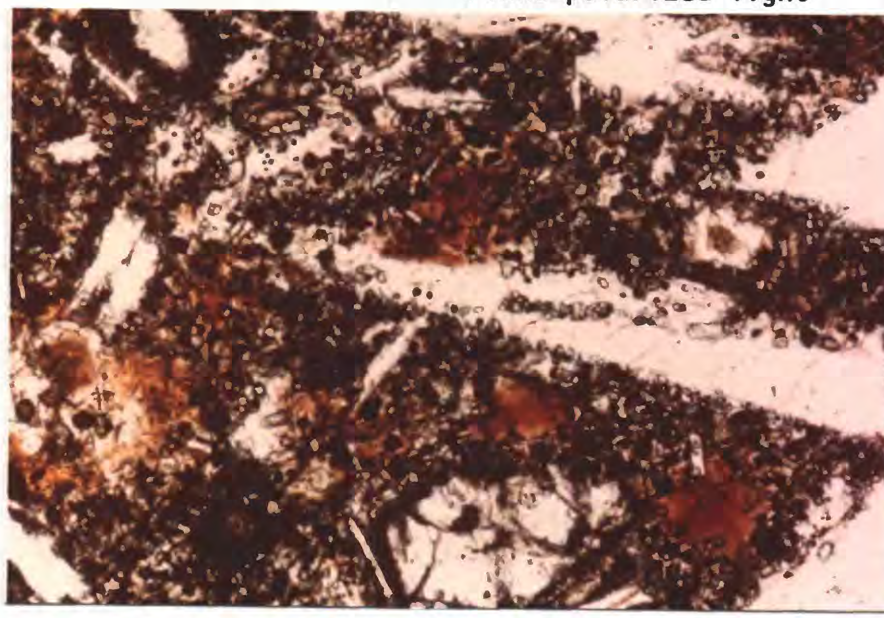
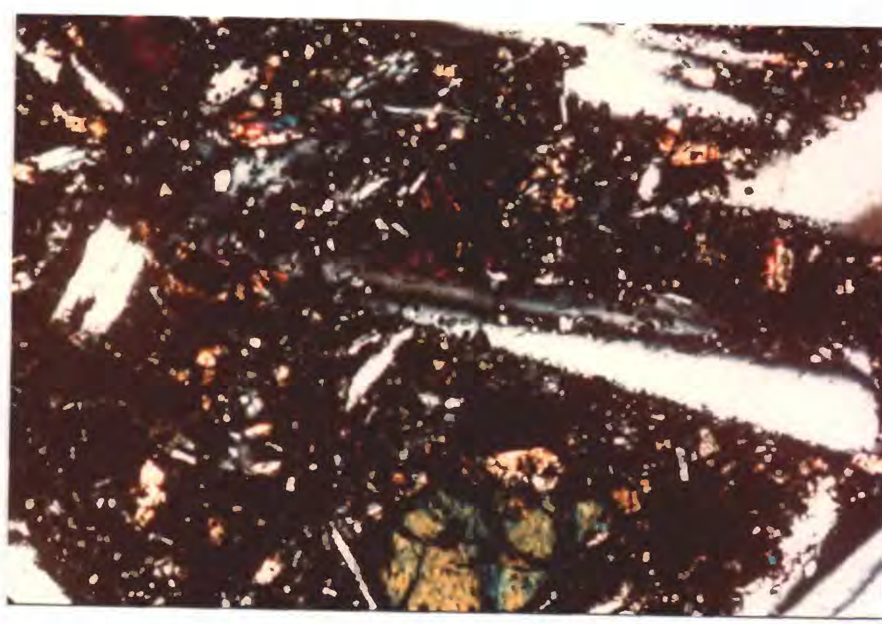


Fig. 25.--INTERGRANULAR TEXTURE.--The angular interstices between the plagioclase laths are occupied by olivine, augite, and magnetite.

Plane-polarized light



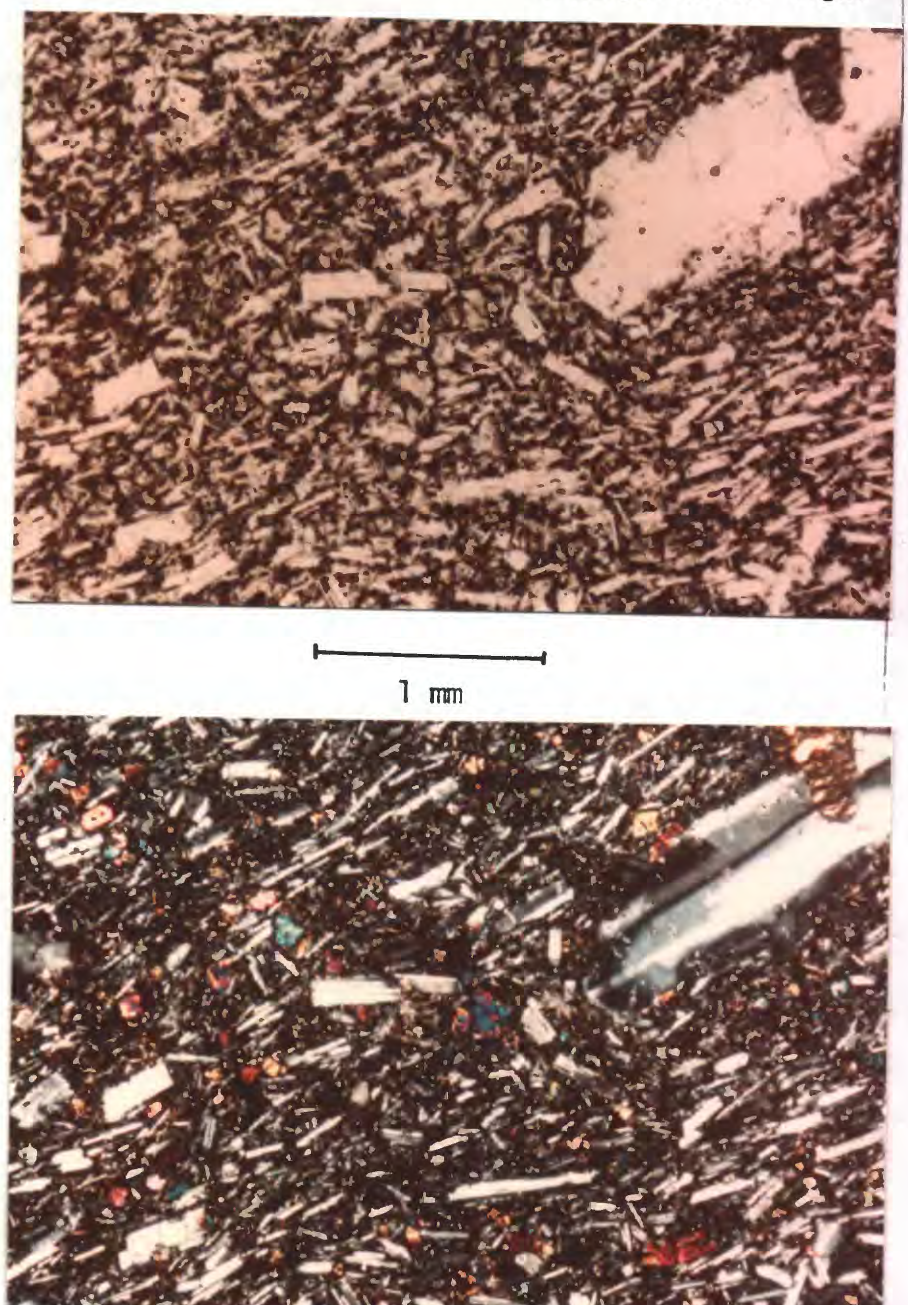
1 mm



Polarizers crossed

Fig. 26.--INTERSERTAL TEXTURE.--Interstices between plagioclase laths are occupied by glass.

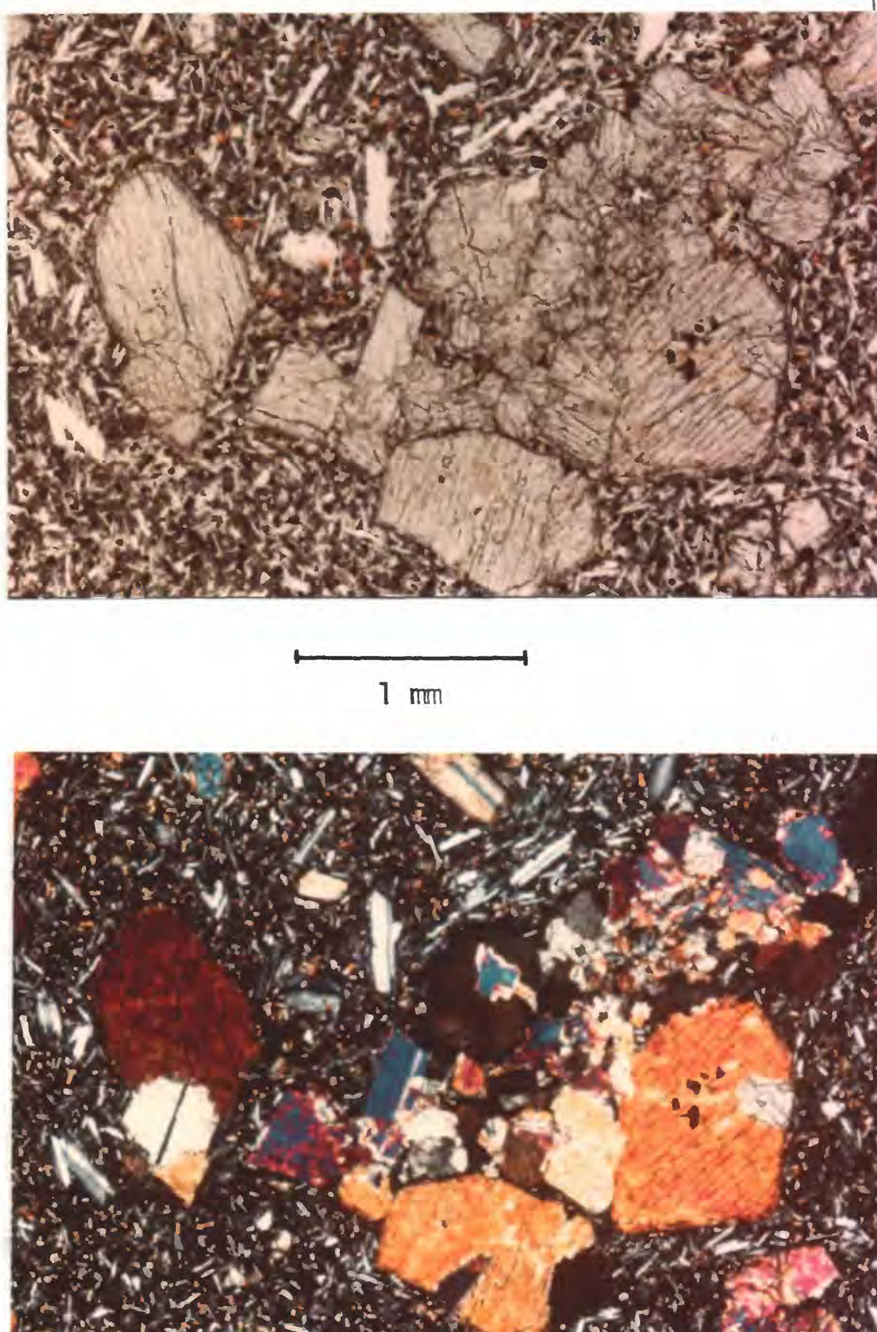
Plane-polarized light



Polarizers crossed

Fig. 27.--TRACHYTIC TEXTURE.--Microlites of olivine, pyroxene, and magnetite surround plagioclase laths which are oriented in a subparallel manner.

Plane-polarized light



Polarizers crossed

Fig. 28.--GLOMEROPORPHYRITIC TEXTURE.--Phenocrysts of augite gather in clumps and are surrounded by microlites of plagioclase, pyroxene, and magnetite.

Representative samples of the oliine basalt from the four localities are quite similar and consist of the following minerals listed in order of decreasing abundance as determined by point counting and visual estimations.

MINERAL	AVERAGE PERCENTAGE	PERCENTAGE RANGE
Plagioclase	55	50-80%
Olivine	25	10-30%
Clinopyroxene	10	5-20%
Magnetite	5	1-20%
Glass	5	1-10%
Alteration products	2	0-5%

Plagioclase.--Plagioclase is the dominant mineral and forms euhedral laths that show little alteration. The composition of phenocrysts for three size ranges were determined by maximum extinction angles on albite and carlsbad-albite twins cut normal to (010).

.5 mm	An 45+(?) to 50	Andesine
.5 mm to 2.0 mm	An 45 to 60	Andesine-Labradorite
2.0 mm	An 55 to 75+	Labradorite-Bytownite

The composition of the very small groundmass plagioclase ranges from $An_{40(?)}$ to greater than An_{50}. In the phenocrysts, albite-twinning is most common with smaller numbers of carlsbad and carlsbad-albite twins. Both normal and reversed zoning were observed in pehnocrysts of the basaltic andesite.

Olivine.--The olivine crystals are usually equant, but occasionally they are elongated parallel to the c axis. The majority of the grains are subhedral to anhedral, although a few euhedral crystals were noted. Embayed or corroded margins were not observed on the olivine crystals; however, many margins and fractures are commonly altered to form iddingsite (fig. 29), serpentine, clay minerals, and iron oxides. Distinct kink bands were observed in a few large grains which may be xenocrysts. The optical axial angle ($2V_z$) extimated from interference figures ranges from 70 to 90 degrees with values clustering about 85 degrees. Zoned crystals with rims appearing to be more fayalitic are scarce, but no electron microprobe determinations were made to confirm the zoning. In addition, the olivine phenocrysts contain small inclusions of picotite (brown in plane polarized light) and equant grains of magnetite.

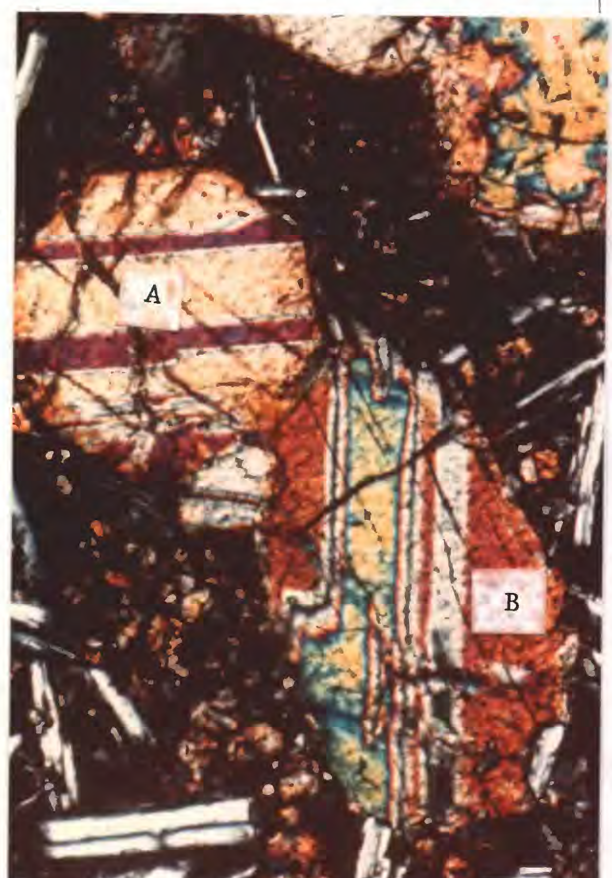
Clinopyroxene.--Short prismatic crystals of augite are the dominant pyroxene phenocrysts. Occasionally the groundmass pyroxenes exhibit extinction angles close to 35 degrees suggesting the presence of pigeonite or subcalcic augite. The augite appears pale brown in plane polarized light with a few crystals exhibiting weak pleochroism(?). The extinction angle c z ranges from 40 to 52 degrees, and the estimated optic axial angle ($2V_z$) is about 55°. Twins with (100) as twin-plane are occasionally present (fig. 30). Chlorite and limonite are present along altered margins. Small inclusions of olivine, plagioclase, and magnetite are found in some of the larger phenocrysts.

Magnetite.--Magnetite, the most abundant oxide mineral, ranges from 1 to over 20 percent of the rock with 5 percent the average value. It is restricted to the groundmass and typically occurs as small triangular, square, and rhombus-shaped grains attaining diameters of approximately 0.25 mm. Weathered grains are usually rimmed with red hematite and/or limonite. When the magnetite grains are associated with the volcanic glass they are often larger but less abundant and contrast well with the brown volcanic glass (fig. 31).

Plane-polarized light

Fig. 29.--Olivine crystal partly altered to iddingsite, serpentine, and hematite.

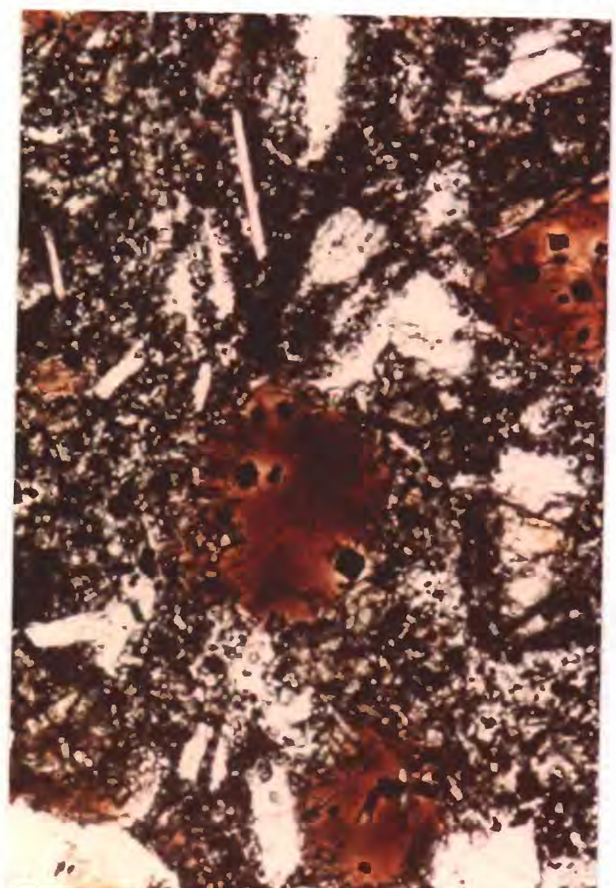
Polarizers crossed



.25 mm

Fig. 30.--Augite phenocrysts twinned on (100). (A) sectioned normal to the twin plane. (B) sectioned oblique to the twin plane.

Plane-polarized light



.25 mm

Fig. 31.--Euhedral grains of magnetite are enclosed by pale brown glass.

Glass.--The glass appears light-brown and varies in abundance from 1 to 5 percent. A transparent yellow-brown alteration product identified as palagonite is associated with the glass.

Secondary minerals.--Secondary minerals found associated with the volcanic rocks are subdivided into two categories as follows: (1) alteration products of primary minerals, and (2) those formed as interstitial and amygdaloidal fillings. These aresummarized in tables 1 and 2.

TABLE 1

SECONDARY MINERALS FORMED AS ALTERATION PRODUCTS OF PRIMARY MINERALS

Primary Minerals	Alteration Products	Characteristics	Means of Identification
Plagioclase	Montmorillonite	greenish	X-ray
Plagioclase (megacrysts)	Clay+Saussurite	white greenish	X-ray/optical
Pyroxene	Chlorite	greenish rim	optical
Olivine	Iddingsite/ Serpentine	Surrounds olivine xls and fractures	optical
Magnetite	hematite limonite-trace	translucent red rims	optical

TABLE 2

SECONDARY MINERALS FOUND AS AMYGDALOIDAL AND INTERSTITIAL FILLINGS

Mineral	Occurrence Basalt (B) Tuffs (T)	Amygdaloidal (A) Interstitial (I)	Means of Identification
[1]Zeolites			
Natrolite	B	A	Oral commun.*
Mesolite	B	A	X-ray+
Calcite	B & T	A	HCl
Chalcedony	B	A	Visual Inspec.
Clay	T	I	Optical
Palagonite	B & T	I & A	Optical

*Dr. Wayne Kartchner (1970)
+Dr. Dana Wagner, U.S. Geological Survey, Menlo Park, California
#P. Aruscavage (see table 3), page .

[1]Zeolite crystals are commonly found as amygdaloidal fillings in basalt, and they range from 1 mm to over 3 cm in length. Although found throughout the area mapped, they are most abundant in the Anderson Reservoir area. The largest occurrence of natrolite is now covered by Anderson Reservoir (W. Kartchner, oral commun., 1970). Mesolite is most abundant 1.5 km southwest of Mud Lake adjacent to the Coyote Fault.

CHEMISTRY

Chemical analyses of a representative selection of pyroclastic rocks and basalts are presented in table 3. These include rapid major element determinations and six-step semiquantitative 30 element spectrographic chemical analyses. In addition, these samples were tested for mercury concentration as part of the San Francisco Bay Regional Study by the U.S. Geological Survey. Whole rock oxide percentages are plotted on a AFM diagram (fig. 32) in which A = $Na_2O + K_2O$, F = FeO (total iron calculated as FeO), and M = MgO. The tuffaceous rocks (GI-4, 5, 8, and 9) were not plotted as individual points but as a cross-hatched field because of their high ignition loss, decrease in alkalis, and possible increase in Al which suggest that they have been chemically altered. Thus, the apparent compositional trend showing an increase in F and A from stratigraphically younger to older rocks is based on tenuous evidence. This differentiation diagram indicates that the tuffs may have andesitic affinities while the basalts plot within the basaltic andesite, and basalt field.

When compared to Hawaiian basalts on the alkali-silica diagram (fig. 33) the basalts (GI-1, 2, 6, and 7) cluster toward the lower boundary that separates the alkali basalts and the high alumina basalts. Kuno (1966) states that the generation of different basaltic magmas is closely related to origin at different depths along the Benioff zone. Since the Anderson-Coyote Reservoir basalts plot well within the alkali basalt field, they correspond to those derived from the greatest depth along the Benioff zone (Kuno, 1966). In addition, the association of mafic and ultramafic xenoliths, fragments of the lower crust-upper mantle, seems consistent with a deep seated origin.

TABLE 3A

ANALYSES OF ANDERSON-COYOTE RESERVOIR VOLCANIC ROCKS

Specimen	Gi-1	Gi-2	Gi-3	Gi-4	Gi-5	Gi-6	Gi-7	Gi-8	Gi-9
escription	Basaltic Andesite	Tholeiitic Basalt	Breccia	Bedded Tuff	Breccia	Basaltic Andesite	Basalt	Tuff	Tuff
SiO_2	48.60	47.60	48.30	54.90	42.80	49.70	47.30	47.00	53.60
Al_2O_3	17.90	16.80	17.80	15.60	13.90	17.70	16.80	13.30	14.30
Fe_2O_3	4.80	3.60	6.70	7.20	6.70	4.90	5.70	5.70	7.00
FeO	4.40	5.80	2.80	0.12	0.88	4.20	3.50	1.40	0.68
MgO	6.70	7.70	6.30	2.40	4.30	6.10	8.20	4.90	4.30
CaO	8.40	8.50	8.20	1.70	11.30	8.10	10.30	6.80	2.70
Na_2O	3.90	3.10	3.20	1.20	1.60	3.90	2.50	1.30	1.00
K_2O	0.98	1.50	0.92	0.96	0.73	1.10	1.50	0.79	0.95
H_2O	1.30	2.59	3.00	13.60	8.50	1.60	2.36	10.70	13.60
TiO_2	0.96	0.88	0.92	0.55	0.57	0.91	0.91	0.56	0.54
P_2O_5	0.51	0.64	0.48	0.16	0.64	0.57	0.61	0.42	0.32
MnO	0.15	0.15	0.15	0.10	0.38	0.10	0.15	0.13	0.07
CO_2	0.02	0.20	0.02	0.01	6.20	0.05	0.03	5.50	0.25
otal	98.62	99.06	98.79	98.50	98.50	98.93	99.86	98.50	99.31

nalysis performed in the Rapid Rock Analysis Laboratories.
nalyst: Lowell Artis

TABLE 3B

CIPW NORMS

Specimen	Gi-1	Gi-2	Gi-3	Gi-4	Gi-5	Gi-6	Gi-7	Gi-8	Gi-9
q	-----	-----	1.92	See[1] page 76		-----	-----		See[1] page 76
c	-----	-----	-----			-----	-----		
or	5.87	8.96	5.50			6.57	8.86		
ab	33.46	26.48	27.41			33.36	21.18		
an	28.84	27.76	31.87			27.84	30.23		
ne	-----	-----	-----			-----	-----		
wo	4.14	3.89	2.51			3.63	7.00		
en	6.42	7.35	15.88			12.00	13.60		
fs	1.08	2.49	-----			1.86	0.33		
fo	7.36	8.42	-----			2.36	4.80		
fa	1.37	3.15	-----			0.40	0.13		
mt	7.06	5.27	6.93			7.18	8.28		
cm	-----	-----	-----			-----	-----		
hm	-----	-----	2.00			-----	-----		
il	1.85	1.69	1.77			1.75	1.73		
ru	-----	-----	-----			-----	-----		
Thorton-Tuttle Differentiation Index	39.34	35.43	34.83			38.93	30.06		

TABLE 3C

SEMIQUANTITATIVE 6-STEP SPECTROGRAPHIC ANALYSIS (ppm)

Specimen	Gi-1	Gi-2	Gi-3	Gi-4	Gi-5	Gi-6	Gi-7	Gi-8	Gi-9
Fe%	7.0	7.0	10.0	7.0	7.0	7.0	7.0	5.0	5.0
Mg%	5.0	5.0	5.0	1.0	2.0	5.0	5.0	3.0	2.0
Ca%	5.0	7.0	5.0	1.5	10.0	5.0	7.0	7.0	2.0
Ti%	1.0	1.0	1.0	0.7	0.7	1.0	1.0	0.7	0.5
Mn (ppm)	1000	1000	1000	700	2000	1000	1000	1000	1000
B	N	N	N	20	N	N	N	50	20
Ba	200	500	300	300	300	300	500	2000	300
Be	2	2	2	N	N	2	N	N	N
Co	50	30	50	30	30	30	30	50	50
Cr	300	200	300	150	300	200	300	700	300
Cu	70	100	100	70	70	70	100	100	100
Nb	N	50	20	N	20	20	50	30	N
Ni	200	200	200	150	200	150	200	300	300
Sc	30	20	30	20	20	30	30	20	20
Sr	300	500	300	150	300	300	700	500	200
V	200	150	150	70	150	150	150	150	100
Y	50	20	30	20	20	50	20	20	15
Zr	200	150	200	150	150	200	150	100	100
Si%	G	G	G	G	G	G	G	G	G
Al%	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Na%	1.5	1.0	1.0	0.5	0.7	1.5	1.0	0.7	0.5
K%	1.0	1.5	1.0	1.0	1.0	1.0	1.5	1.0	1.0
P%	N	N	N	N	N	N	N	N	N
Ga	20	20	20	20	20	20	20	20	15
Yb	3	2	3	2	2	3	2	2	2

TABLE 3D

MERCURY CONCENTRATION (ppb)

Specimen	Gi-1	Gi-2	Gi-3	Gi-4	Gi-5	Gi-6	Gi-7	Gi-8	Gi-9
Hg	10	28	14	56	120	14	18	26	82

Analytical Services & Research, Reston, Virginia.
Analyst: P. Aruscvage.

[1]CIPW norms were not calculated for the pyroclastic rocks Gi-4, 5, 8, and 9 for the following reasons: These rocks showed high ignition loss, leaching of MgO, Na_2O and some CaO while alumina reflected little change suggestinig some argillization. In addition, oxidized iron is high while FeO is low indicating a high degree of oxidation. An explanation why altered rocks were submitted for analysis is given on page 94.

[2]Si, Al, Fe, Mg, Ca, Na, K, Ti, and P are reported in %; all others in ppm.
G = Greater than 10%, or greater than value shown.
N = Not detected, at limit of detection or at value shown.
Analytical Laboratories, U.S. Geological Survey. Analyst: R. E. Mays.

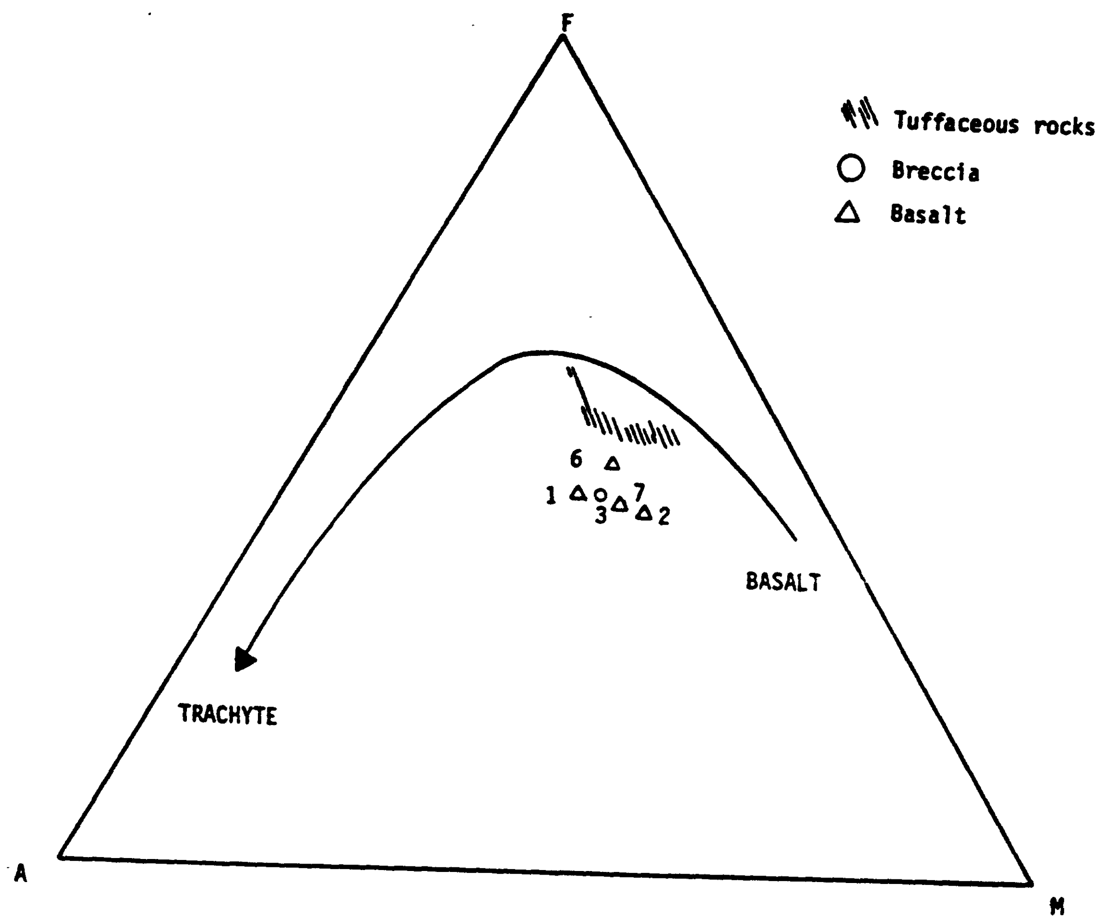


Fig. 32.--AFM plot for analyzed Anderson-Coyote Reservoir volcanic rocks.

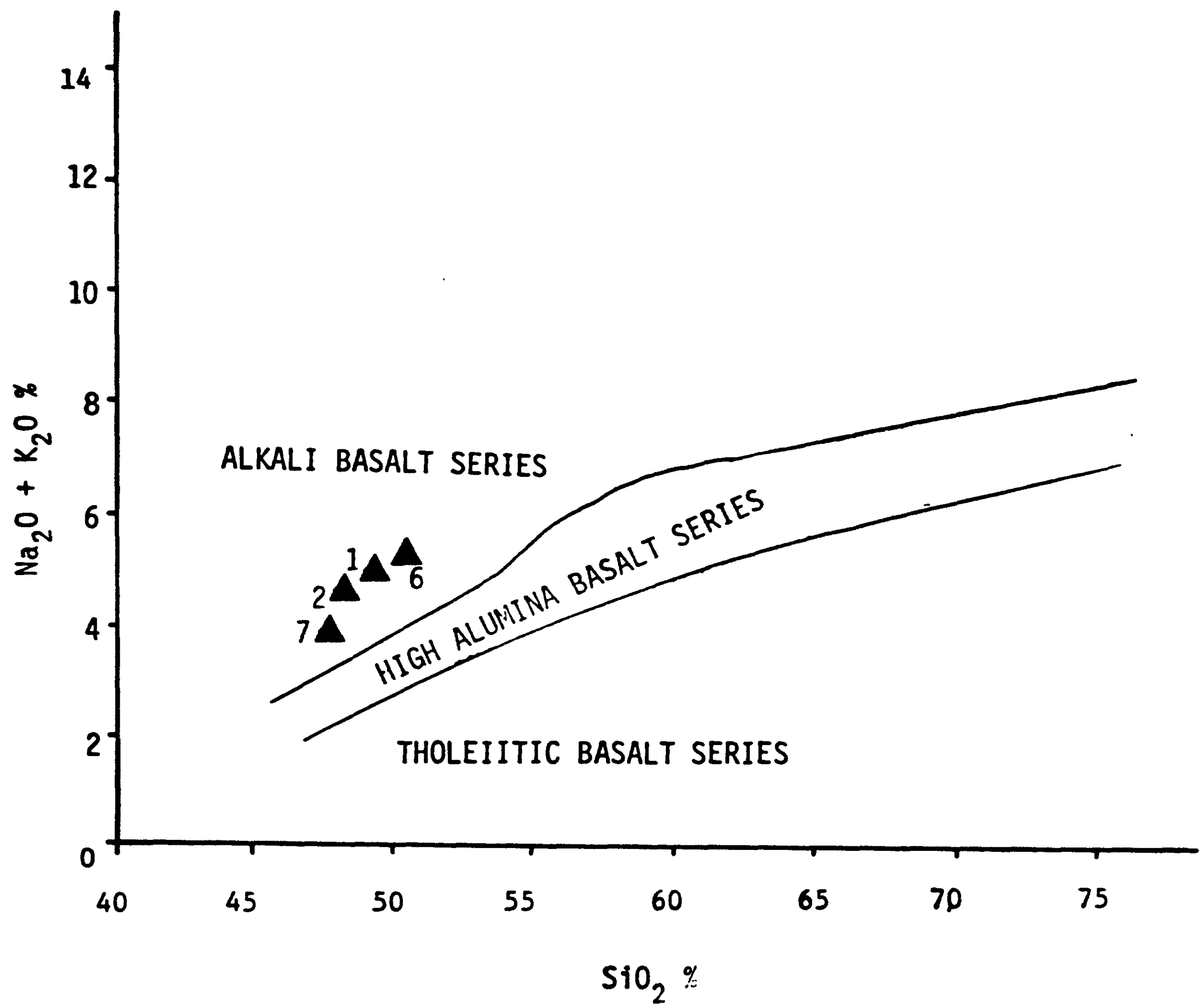


Fig. 33.--Alkali weight percent versus SiO_2 percent diagram for separating the basaltic rock series into three divisions (after Kuno, 1966-for Hawaiian rocks).

CIPW norm calculations (table 3) indicate the basalts are silica undersaturated. The classification of Yoder and Tilley (1962) requires that olivine and nepheline be present in the norm for the rock to be considered an alkaline basalt. However, the presence of olivine and hypersthene and the lack of nepheline place them in the olivine-tholeiite basalt field (Yoder and Tilley, 1962). When plotted on the normative CPX-Ol-Ne-Qtz tetrahedron of Yoder and Tilley (1962), the basalts plot in the olivine-tholeiite field and fall between the plane of silica saturation (CPX-OPX-Pl) and critical plane of silica saturation (CPX-Ol-Pl).

The nature of the suite is further illustrated by the Thornton and Tuttle variation diagram and Nockold's averages (fig. 34). The position of the Anderson-Coyote Reservoir volcanic rocks are plotted over contours on a frequency distribution diagram prepared from 5,000 analyses in H. S. Washington's tables (1917). When these rocks are compared to average compositions of various rock types calculated by Nockold (1954), they plot closest to alkali andesites and alkali basalts. In addition, the differentiation index (the sum of Petrogeny's Residua System) when plotted against the appropriate silica percentage may be used to measure a rock's basicity. This shows the basalts and breccia to be generally undersaturated.

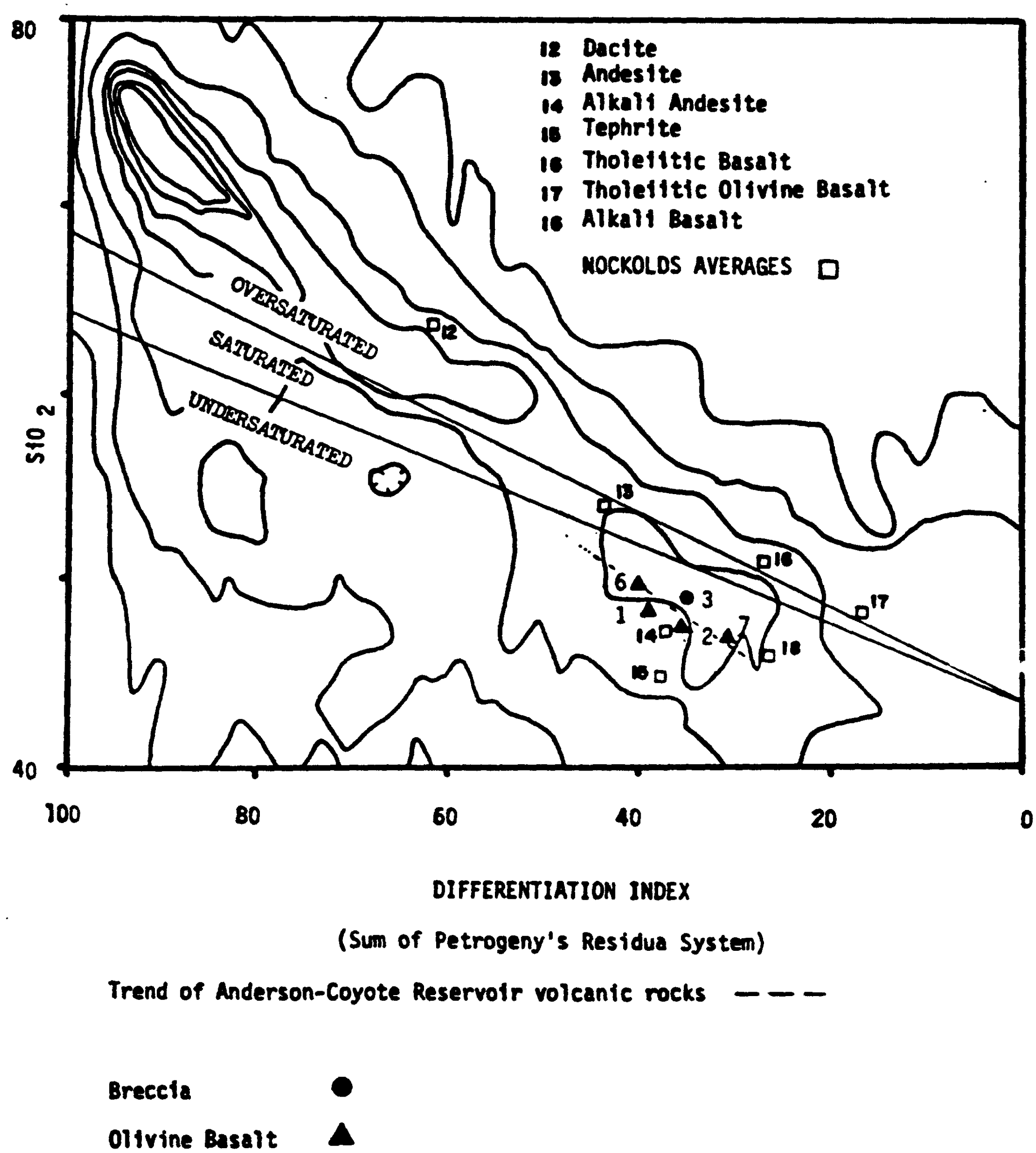


Fig. 34.--Differentiation trend for the Anderson-Coyote Reservoir volcanic suite as determined by utilization of the differentiation index of Thornton and Tuttle (1960). Background contours indicate frequency distribution of the silica-differentiation-index values for 5,000 analyses in H. S. Washington's tables (from Thornton and Tuttle, 1960).

SUMMARY OF PETROGRAPHY AND CHEMISTRY

Discrepancies arise when oxide percentages, CIPW norm calculations, and modal mineralogy are used in basalt classification, because basic definitions differ among authors. When compared to the alkali-silica diagram of Kuno (1966) (fig. 33), the Anderson-Coyote Reservoir basalts are higher in alkalis for a given silica content than the high alumina and tholeiite basalts and plot well within the alkali basalt field. On the other hand, the absence of normative nepheline and the presence of normative olivine and orthopyroxene above that needed in normative diopside indicates olivine-tholeiite affinities according to Yoder and Tilley (1962). However, both MacDonald and Kuno state that the presence of normative nepheline is not essential to have an alkali basalt if the basalt is undersaturated and high in alkalis. When compared to a world-wide compilation of average chemical compositions of tholeiite versus alkaline basalts, no diagnostic trend for the Anderson-Coyote rocks could be established. Since chemical values may be influenced by secondary mineralization (iddingsite/serpentine surrounding olivine crystals) and weathering, Hyndman (1972) feels modal mineralogy takes precedence in determining basalt type. Mineralogically, the olivine crystals show no reaction with pyroxene indicating that they crystallized simultaneously and in equilibrium, characteristics found in alkaline basalts. In addition, Prowell (1975) reported low values of normative nepheline and called his samples of Anderson-Coyote rocks alkaline basalts. However, the presence of olivine phenocrysts, which can be observed in hand specimen, and the prevalence of augite places them in the modal classification of olivine basalt.

This dilemma of basalt classification will not be addressed here, but the rock names will be qualified by the means used to establish them; they are as follows: alkaline basalt (when compared to oxide percentages of Hawaiian basalts and definitions by Kuno (1966) and Macdonald (1968), tholeiitic basalt to basaltic andesite (when CIPW norms are used and the definitions used by Yoder and Tilley (1962)), and alkaline(?), olivine basalt (when modal mineralogy is used).

XENOLITHS

Ultramafic xenoliths commonly form a world-wide association with undersaturated basalts and regional arcuate belts which occur in both continental and oceanic settings. Their distinctive mineralogy of Mg-rich olivine, enstatite, Cr-diopside, and chrome spinel set them apart from the enclosing basalt. They are thought to originate in the upper mantle and lower crust; consequently, they may represent unfused residues of mantle rock from which basaltic magma has already been extracted.

The distribution of xenolithic basalts in the southwestern United States shows a scarcity of known localities along the central Pacific coast (H. G. Wilshire, oral commun., 1975). It is for this reason that the xenoliths associated with the Anderson-Coyote Reservoir basalts represent an important locality.

Xenoliths are most abundant in basalts southwest of Coyote Dam and adjacent to Coyote Reservoir. These two localities, designated Gilroy 1 and 2 (GI-1 and GI-2), are diagrammatically indicated on the geologic map. At GI-1 the mafic and ultramafic xenoliths are enclosed in a massive olivine basalt which represents a feeder vent for the basaltic rocks. The inclusions at GI-2 are found within basalt fragments in colluvium. The xenoliths range from 1 to 3 cm in diameter. They are subangular to subrounded and are occasionally bounded by planar facets.

Hand specimen modes by visual estimation for each locality are plotted on a plagioclase-olivine-clinopyroxene-orthopyroxene diagram (fig. 35, 36). For

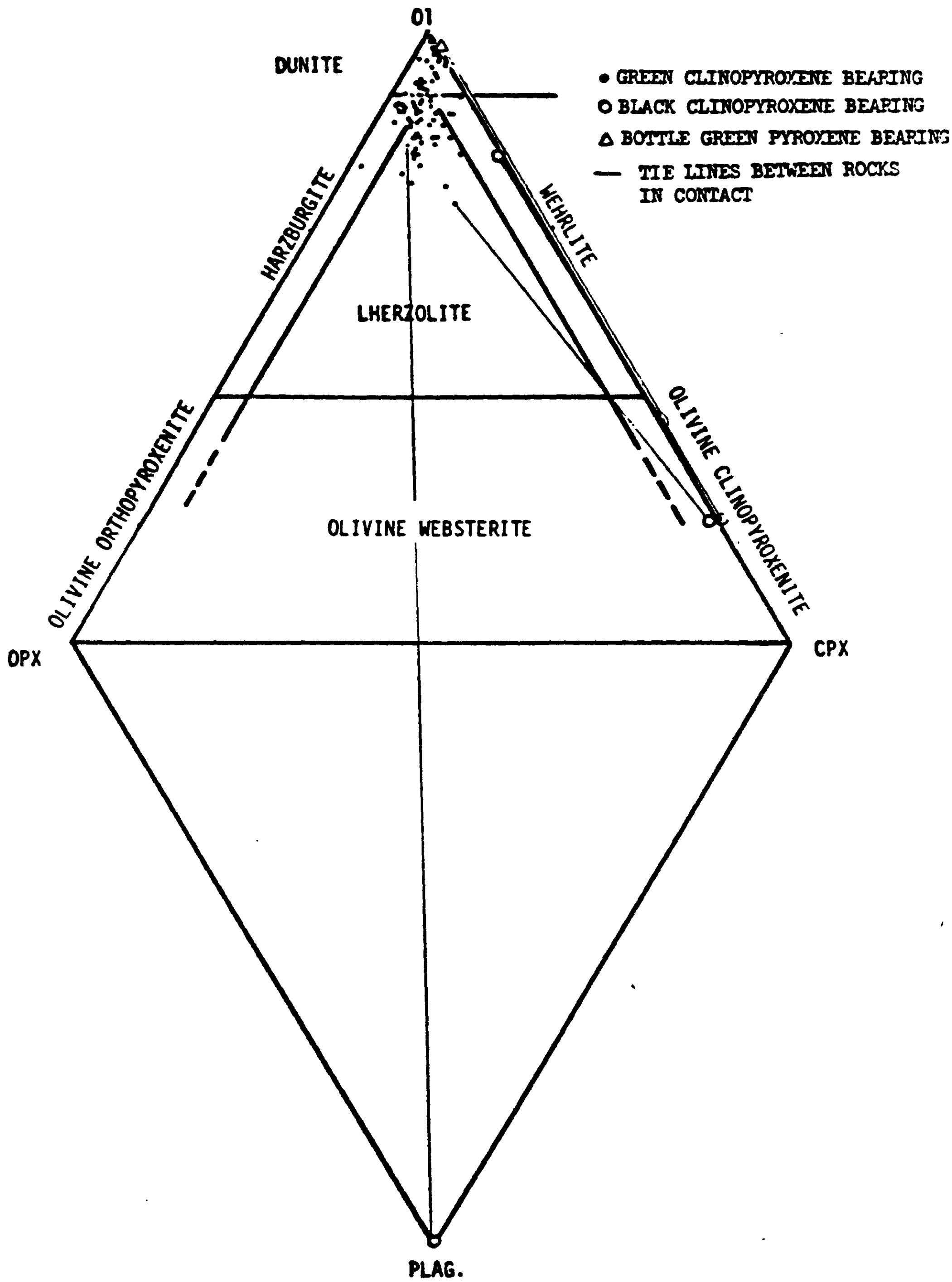


Fig. 35.--Hand specimen modes for GI-1 (counted by Wilshire and Nakata).

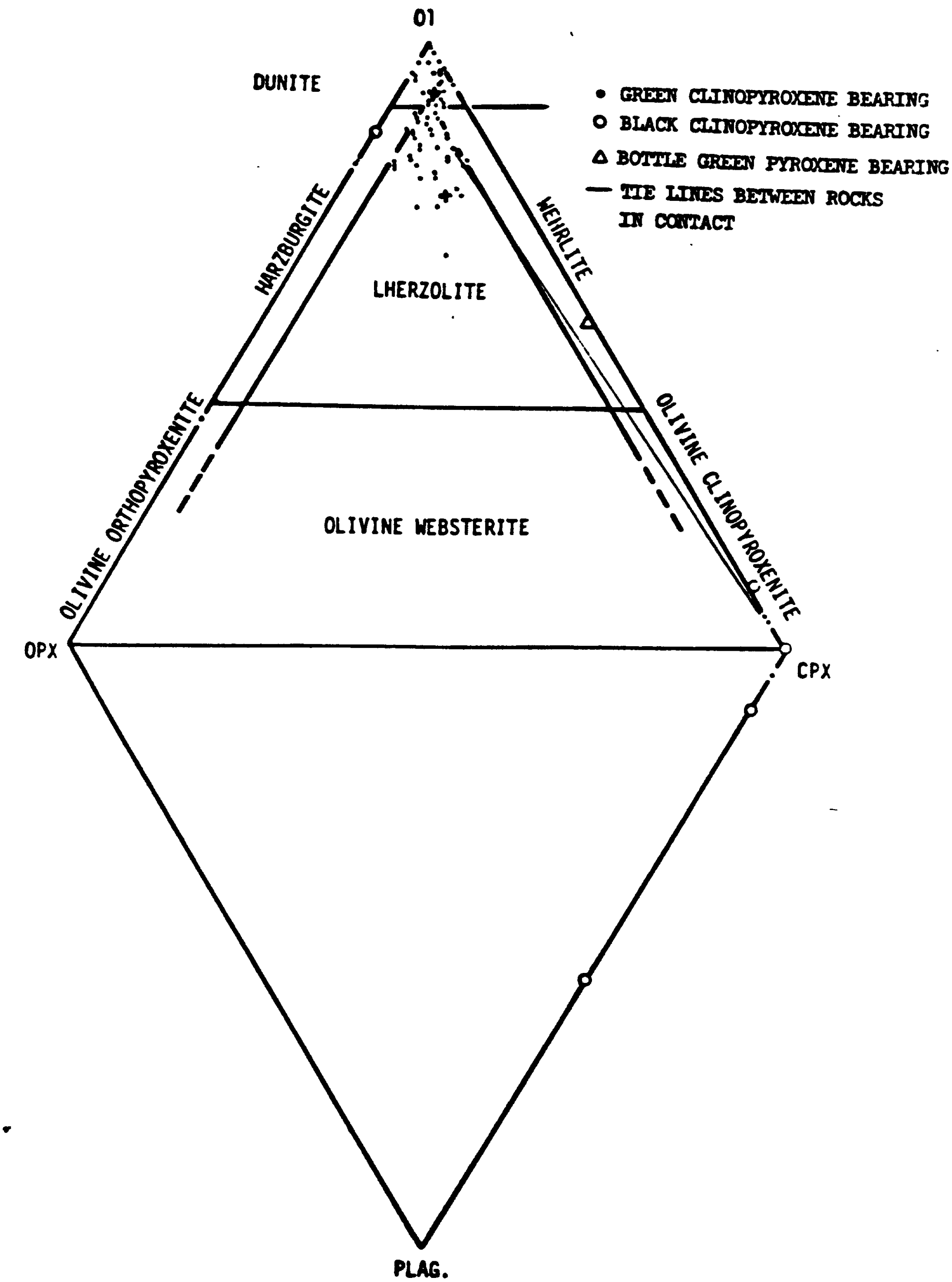


Fig. 36.--Hand specimen modes for GI-2 (counted by Wilshire and Nakata).

each locality Mg-olivine spinel lherzolite and dunite are the dominant peridotites with lesser amounts of harzburgite, wehrlite, and feldspathic lherzolite. The spinel pyroxenites are represented by olivine clinopyroxenite and clinpyroxenite, but are quite rare. Gabbro and metagabbro xenoliths are found locally, and one specimen has a thin metagabbro band in lherzolite.

Peridotite.--The peridotites are composed of four major minerals: light green Mg-olivine approximately Fo_{90} (composition determined by X-ray method of Jackson 1960), dark green clinopyroxene (Cr-diopside), root-beer brown orthopyroxene (hyperthene), and brown spinel. The texture is dominantly metamorphic (tectonite) and may be subdivided further into the porphyroclastic group (Nielson-Pike and Schwarzman, 1977). Plastic deformation is reflected in prominent kink bands (fig. 37) found in the large olivine crystals and less frequently in the orthopyroxenes. Olivine is the least resistant to deformation and is often recrystallized to form a fine-grained matrix.

Only one peridotite (dunite) was inspected in detail. It is essentially bimeralic with olivine comprising approximately 99 percent of the rock and spinel the remaining 1 percent. Although conspicuous by hand lens inspection, dark green pyroxene grains 0.5 to 1 mm in diameter were not found in the thin section, but they probably make up 1 to 2 percent of the rock. The olivine is typically 0.2 to 2.5 mm in diameter and is altering to iddingsite along fractures. Along the margin of the xenolith the olivine is commonly embayed and shows reaction with the enclosing basalt reflecting a non-equilibrated condition. The spinels are non-uniform in distribution and occur as relatively large (0.1 to 1.5 mm in diameter) crystals. They range in color from bronze to dark brown in plane polarized light.

Olivine pyroxenite.--The olivine pyroxenite is chiefly composed of two to three minerals. Black clinopyroxene is the dominant mineral with varying

Polarizers crossed

Fig. 37.--Prominent kink bands in olivine reflecting plastic deformation.

amounts of a dark brown Fe-rich olivine Fo_{50} (typical value reported by C. E. Meyers, U.S. Geological Survey, Menlo Park, California) and green spinel. The presence of orthopyroxene exsolution lamallae and euhedral grain shapes may reflect an igneous texture.

Gabbro and metagabbro.--These rocks are composed mainly of plagioclase and clinopyroxene. They are fine grained with minerals not exceeding 1 mm in diameter. The metagabbro shows a preferred orientation of minerals with the long dimension concentrated in the plan of foliation.

Composite xenoliths.--Composite xenoliths occur at both localities, but are quite rare. Of particular interest is one with a metagabbro vein cutting a spinel lherzolite and another with a pyroxenite band in contact with a peridotite. Thin-section examination of the vein shows alignment of plagioclase laths which suggests that the lherzolite predates the metagabbro. Wilshire and Trask (1971), and Wilshire and Shervais (1975) have concluded that these bands represent igneous segregations from the parent peridotite magma which have been injected as veins.

Megacrysts.--Large crystals (megacrysts) of Fe-rich olivine Fo_{50} (typical value reported by H. G. Wilshire, oral commun., 1975), plagioclase, and clinopyroxene are found in association with the ultramafic inclusions. Of the three types recognized, plagioclase, and rarely Fe-olivine exhibits crystal faces while the margins of both olivine and clinopyroxene appear rounded suggesting a disequilibrium with the enclosing basalt. In addition to the Anderson-Coyote Reservoir area, a recurring world-wide association of undersaturated basalt, ultramafic xenoliths, and their megacrysts, may reflect a high-pressure genetic relationship between them (Wilshire and Shervais, 1975). The following table summarizes the characteristics of megacrysts which are listed in decreasing order of abundance.

TABLE 4

MEGACRYSTS

Mineral	Abundance	Color	Dimension of Largest Found	Comp.
clinopyroxene	abundant	dark greenish black	30 mm x 15 mm	?
plagioclase	moderately abundant	translucent to milky-white	7 mm x 6 mm	An 65 72*
olivine	rare	brown	25 mm x 25 mm	Fe-rich

*Composition determined by X-ray method of Smith, J. R., and Yoder, H. S., Jr. (1956).

GEOLOGIC HISTORY OF THE ANDERSON-COYOTE RESERVOIR VOLCANIC ROCKS

Volcanic eruptions started in the Anderson-Coyote Reservoir area approximately 3.5 m.y. ago (A. Sarna-Wojcicki, oral commun., 1973). The eruptions were concentrated along the trace of the Calaveras Fault zone suggesting the magma may have used the fault planes as conduits to the surface. A deep seated magma source may be inferred from the basalt chemistry and the inclusion of upper mantle fragments (ultramafic xenoliths).

Following the Pliocene uplift, lowland areas were receiving coarse sediments eroded from the adjacent terrain. These loosely consolidated gravels and sands (Santa Clara Formation) became the base on which the volcanic rocks were deposited. In the intervening areas where the gravels had not been deposited, the volcanic rocks were unconformably deposited on the older serpentinite, Franciscan assemblage, and Great Valley rocks.

Two types of eruptions produced the Anderson-Coyote Reservoir volcanic rocks: (1) EXPLOSIVE, which produced the tuffs and breccias, and (2) EFFUSIVE, which consisted of relatively quiet outpourings of lava. Based on the stratigraphic evidence, explosive eruptions were dominant in the Late Pliocene with a transition to effusive activity with the passage of time.

According to MacDonald (1972), deposits of ash and lapilli size fragments are diagnostic of explosive eruptions. The dominance of fine tephra in the early deposits of the volcanic sequence suggests that the initial stages of volcanic activity were quite explosive. Field evidence supports this hypothesis as ash formed deposits of lithic, vitric, and crystal tuffs in the outlying areas while poorly sorted breccias were deposited adjacent to the vents. Many of the tuffaceous beds show graded bedding and are associated with accessory lithic fragments and organic detritus indicating deposition in a lacustrine environment (contemporaneously with Santa Clara sands and silts).

Lacustrine deposition may be inferred from the presence of water-laid tuffs and plant material along bedding planes. The existence of lakes may have played an important role in the formation of the volcanic rocks in the following ways: (1) steam generated from the interaction of water saturated sediments and the ascending magma may have combined with magmatic explosions to enhance discharge of tephra in the form of phreatomagmatic eruptions, and (2) the presence of water may have accelerated the transformation of the basaltic ash to palagonite.

Following ash and lapilli agglomerate, the dominant rock type is breccia (agglomerate), indicating a slight decrease in eruption explosiveness. Breccias often show the greatest accumulation adjacent to vents (Hyndman, 1972) as the greater weight of fragments prevents wide distribution. This may be used to infer that the greatest accumulations of the breccias correspond to the venting areas. The breccia west of Coyote Creek, section 4-4' (plate 1) forms a linear outcrop pattern indicating a fissure type vent. The nonsymmetrical distribution of the breccias in the Anderson Dam area (I) and the Coyote Reservoir area (III) may have resulted from inclined venting of the tephra or strong winds which may have caused localization of deposits. No breccias were recognized in the San Felipe Lake area (IV).

As the magma became progressively depleted in silica and enriched in magnesium with respect to iron (fig. 32), there was a systematic increase in fluidity (decrease in viscosity). According to MacDonald (1972), this decrease in viscosity is accompanied by a decrease in explosive eruptions. In addition, the presence of fusiform bombs (fig. 24) is an indication that volcanism is in its waning stages (MacDonald, 1972).

The last stages of volcanism were characterized by relatively quiet effusive eruptions of basalt flows interspersed with sporadic explosive eruptions. These flows were partially controlled by topography as suggested by the variable thicknesses of flows seen in figure 11.

Following the volcanic activity, deposition of the gravels and sands of the Santa Clara Formation continued until the late Pleistocene at which time folding occurred in response to northeast-southwest compression. Subsequent movement on the cross faults (?) and the Calaveras Fault zone, accompanied by erosion and weathering accounts for the present spatial distribution and physical characteristics of the Anderson-Coyote Reservoir volcanic rocks.

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APPENDIX

LOCATIONS AND MEGASCOPIC FEATURES OF CHEMICALLY ANALYZED SAMPLES

Note: Thin sections of rocks to be analyzed were inspected prior to submission to ensure fresh samples; however, these rocks were lost by the U.S. Geological Survey analytical laboratory. The second set of samples were hastily submitted without the benefit of thin section inspection; consequently, many of the pyroclastic rocks analyzed were altered rocks. For locations see plate 1.

GI-1 Olivine basaltic andesite

LOCATION: Coyote Lake area (III) at vent area. Sample from road cut.

MEGASCOPIC FEATURES: The basalt is slightly porphyritic with livine and plagioclase phenocrysts easily seen on and plagioclase phenocrysts differentially weather and form pits. Fresh surfaces are bluish-black, but weather to off-white. Peridotite xenoliths and megacrysts of olivine and plagioclase are common.

GI-2 Olivine tholeiite

LOCATION: Coyote Creek area (II). Sample was collected 1 km southwest of Coyote Dam in colluvium.

MEGASCOPIC FEATURES: The sample is porphyritic, bluish-black on fresh surfaces, but weathers to a yellowish-white. All rocks at this site are fractured due to folding. Peridotite xenoliths are common, but are quite weathered and form cavities. Fresh xenoliths are rare, but are found occasionally.

GI-3 Basaltic breccia

LOCATION: Coyote Lake area (III). Sample from drill core #2, (40') drilled at 45 degrees from the horizontal, in vent area.

MEGASCOPIC FEATURES: The matrix is tan and contrasts well with the darker semirounded clasts of porphyritic basalt. The clast diameter measured on the core surface ranged from 1 to 4 cm. No recognizable bedding features were identified.

GI-4 Tuff

LOCATION: Coyote Lake area (III). Vertical drill core #6 at 55 feet. One of 8 cores drilled perpendicular to the major folded structure.

MEGASCOPIC FEATURES: The sample is tan to off-white, well lithified, but appears slightly weathered. Good graded bedding with thicknesses ranging from 2 to 25 cm. Clasts of vesicular and porphyritic basalt 0.5 m to 1 cm in diameter are concentrated in lower horizon.

GI-5 Tuff breccia

LOCATION: Coyote Lake area (III). Vertical drill core #5 at approximately 55 feet. One of 8 cores taken perpendicular to the major folded structure.

MEGASCOPIC FEATURES: The sample is off-white, well lithified, and appears slightly weathered. No bedding feature was recognized. Sorting is poor.

GI-6 Basaltic andesite

LOCATION: San Felipe Lake area (IV) 0.3 km northwest of San Felipe Lake. Sample taken from small outcrop on west side of ridge.

MEGASCOPIC FEATURES: Bluish-black on fresh surface, but weathers to a brownish gray. Slightly porphyritic, with small ultramafic xenoliths found locally.

GI-7 Olivine basalt

LOCATION: Anderson Dam area (I). Sample taken near exposure of large columnar joints.

MEGASCOPIC FEATURES: The sample is bluish-black on fresh surfaces, but weathers to gray. The porphyritic texture can be seen wit the unaided eye as olivine and plagioclase phenocrysts stand out conspicuously. Some vesicles are filled with secondary minerals.

GI-8 Tuff

LOCATION: Coyote Creek area (III) 0.4 km west of Coyote Dam. Sample collected below roadcut on headward eroding gully.

MEGASCOPIC FEATURES: Tan on relatively fresh surface. Graded bedding distinct with thicknesses ranging from 2 to 15+ cm.

GI-9 Tuff

LOCATION: Coyote Lake area (III). Sample taken from roadcut 0.5 km east of the valley floor on Roop Road.

MEGASCOPIC FEATURES: Off-shite, well lithified, but locally crumbly and slightly weathered. No recognizable bedding features.