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REGIONAL STRATIGRAPHY, K–Ar AGES, AND TECTONIC IMPLICATIONS OF CENOZOIC VOLCANIC ROCKS, SOUTHEASTERN CALIFORNIA

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ABSTRACT. Volcanic and volcaniclastic rocks of early-to-mid Cenozoic age crop out within linear mountain ranges of southeastern California, east of the San Andreas fault. Regional mapping and 32 newly obtained K–Ar age determinations disclose a tripartite stratigraphic division of major volcanic rock units at individual volcanic centers. From oldest to youngest, the stratigraphy includes: (unit A) a basal sequence of basaltic to rhyodacitic lava flows and breccia dated at 26 to 35 m.y.; (unit B) rhyodacitic to rhyolitic lava flows, domes, volcaniclastic rocks, including several major ignimbrite sheets. These rocks yield ages largely in the range of 22 to 28 m.y.; and (unit C) mafic lava flows that are divided into two subunits dated at 25 to 29 m.y. (unit Ca) and 13 to 22 m.y. (unit Cb). Plutonic rocks with K–Ar ages between 21 and 26 m.y. intrude unit A in the Chocolate Mountains and may be present at depth beneath many of the major volcanic centers in the region.

The volcanic rocks of units A and B are classified as calc–alkaline based on major-element abundances. They are characterized by a slight excess of K_2O *"over"* Na_2O. Volumetrically these lavas are largely of silicic composition with a subordinance of andesite. Volcanic rocks of unit C range in composition from hypersthene normative basalt to quartz normative andesite and dacite. They have relatively high Al_2O_3 and slightly high TiO_2. $K_2O \div Na_2O + K_2O$ averages 0.35.

Volcanism commenced in southeastern California about 33 m.y. ago following a pronounced early Cenozoic magmatic hiatus that may mark the presence of a proto-San Andreas fault system in coastal California. Oligo-Miocene age volcanic rocks of the region overlap in age with dated volcanic rocks of Arizona and New Mexico. These rocks probably record an early Cenozoic subduction system off the coast of the Western United States. The age of termination of subduction in southeastern California is inferred to be slightly older than 22 to 25 m.y. A transition to mafic and intermediate volcanism in the region is dated at 13 to 19 m.y. This age is significantly younger than the generally cited age of transition to basaltic volcanism in the southwestern United States and the probable age of inception of basin-range faulting. The dated volcanic transition overlaps in time with the probable age of inception of the San Andreas system in southern California.

The Salton Creek fault is a major east-west trending fault of southeastern California. It was active during mid-Cenozoic time and marked the northern boundary of the Cenozoic volcanic and plutonic province. The fault ceased to be a major boundary during mid-Miocene time, inasmuch as it is overlapped by mafic volcanic rocks of mid Miocene age. The Salton Creek fault is parallel to and may be an ancestral element of the Transverse Range structural province.

INTRODUCTION

Volcanic rocks of known and presumed Cenozoic age crop out over much of southern California east of the San Andreas fault and south of the Garlock fault within the Mojave and Colorado Deserts (fig. 1). Their distribution in this broad region is known largely from reconnaissance mapping, but little is known about their petrography, chemical characteristics, and K–Ar ages. In the Mojave Desert, volcanic rocks are exposed slightly less than 30 km from the San Andreas fault (Tropico Volcanics of Dibblee, 1967a), and the volcanic fields of the Newberry and Bullion

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Mountains lie over 65 km from the fault (southeast of Barstow, fig. 1). The Neenach and associated volcanic rocks at Fairmont Butte are juxtaposed against and lie closely adjacent to the San Andreas fault. These are offset by right-slip on the fault from the Pinnacles Volcanic field located approx 300 km to the northwest (Turner, 1969; Matthews, 1973, 1976; Huffman, Turner, and Jade, 1973). Cenozoic volcanic rocks, with the exception of minor basalt, are conspicuously absent from the eastern Transverse Ranges (fig. 1). South of the Transverse Ranges, Cenozoic volcanic rocks closely adjacent to the San Andreas fault are exposed throughout the Chocolate Mountains and adjacent ranges to the east (fig. 1; Crowe, 1973).

Several years ago we began an investigation in southeastern California of the early history of the San Andreas fault and of the geologic history of this unknown region (Crowell, 1973; Haxel and Dillon, 1973; Crowe, 1973; Haxel, ms; Dillon, ms). As an extension of an early part of this work, we chose to study the widespread Cenozoic volcanic rocks of southeastern California for two reasons: First, the age and petrologic character of the volcanic rocks were unknown. Such information on a regional scale is critical to test and refine present models for the evolution of Cenozoic volcanism in the western United States and their relationship to Cenozoic plate interactions. Second, the proximity of the

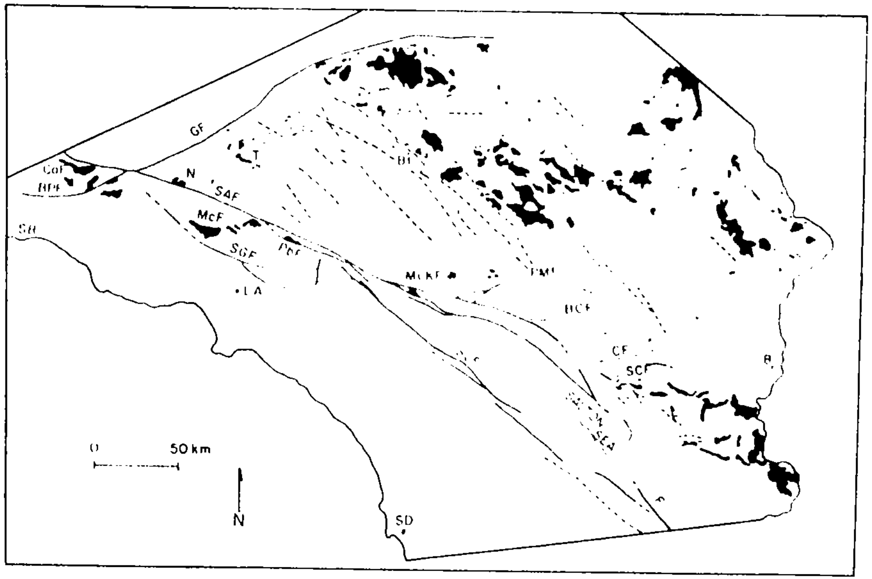


Fig. 1. Distribution of Tertiary volcanic rocks in southern California. Modified from Jennings (1973). SB: Santa Barbara; LA: Los Angeles; SD: San Diego; B: Blythe; Bt: Barstow; IF: Imperial Fault; SJF: San Jacinto Fault; SAF: San Andreas Fault; BPF: Big Pine Fault; SGF: San Gabriel Fault; SCF: Salton Creek Fault; CF: Chiriaco Fault; BCF: Blue Cut Fault; PMF: Pinto Mountain Fault; GF: Garlock Fault. Sedimentary units containing volcanic and volcaniclastic debris include McKF: Mill Creek Formation; PbF: Punchbowl Formation; McF: Mint Canyon Formation; and CaF: Caliente Formation. N: Neenach Volcanic Rocks; T: Tropico Volcanic Rocks.

TABLE 1

K/Ar age determinations of Cenozoic volcanic and plutonic rocks, southeastern California*

Volcanic rocks, southeastern California

SAMPLE NO.	LAB. NO.	%K	%RAD. AR	MINERAL	AGE (M.Y.)	LOCALITY
BASAL VOLCANIC SEQUENCE (UNIT A)						
1) 5-86	KA1190	SEE CROWE (IN PRESS)			31.8±3.2	PICACHO AREA
2) LC-15	KA1263	.80	75.5	PLAG.	25.5±0.2	LITTLE CHUCKWALLA MOUNTAINS
3) AP-2	KA1401	.50	29.4	PLAG.	25.7±1.3	CHUCKWALLA MOUNTAINS
4) F-9	KA1587	3.3	39.0	PLAG.	34.7±1.3	PALO VERDE MOUNTAINS
SILICIC VOLCANIC SEQUENCE (UNIT B)						
5) SW-1	KA1260	0.4	41.1	PLAG.	33.0±1.0	SALTON WASH
6) SW1-3B	KA1290	4.5	62.3	SANIDINE	27.3±0.4	SALTON WASH
7) CG-57	KA1268	.54	30.1	PLAG.	23.5±1.1	IRIS PASS
8) CG-642	KA1264	4.2	69.0	SANDINE	23.7±0.3	IRIS PASS
9) CG-55	KA1267	4.1	59.0	BIOTITE	23.3±0.7	IRIS PASS
10) F-5	KA1590	.22	64.0	PLAG.	35.0±3.0	PALO VERDE MOUNTAINS
11) F-2	KA1589	.63	84.0	PLAG.	25.2±2.5	PALO VERDE MOUNTAINS
12) F-7	KA1583	4.1	44.0	BIOTITE	25.6±1.0	PALO VERDE MOUNTAINS
13) F-1	KA1588	4.8	46.0	BIOTITE	27.9±0.9	PALO VERDE MOUNTAINS
14) F-10	KA1584	1.4	65.0	HRBD.	23.1±0.9	PALO VERDE MOUNTAINS
15) BH-3	KA1410	1.1	50.6	PLAG.	22.1±1.3	BLACK HILLS
16) - -	COL2-7:41A	SEE OLMSTED AND OTHERS (1973)			25.9±0.9	PICACHO AREA
17) - -	COL2-7:38A	SEE OLMSTED AND OTHERS (1973)			24.7±2.1	PICACHO AREA
18) - -	COL-35:1A	SEE OLMSTED AND OTHERS (1973)			26.2±1.6	PICACHO AREA

SAMPLE NO.	LAB. NO.	%K	%RAD. AR	MINERAL	AGE (M.Y.)	LOCALITY
CAPPING VOLCANIC SEQUENCE (UNIT CA)						
19) - -	HC2-15:35B	SEE OLMSTED AND OTHERS (1973)			25.1±1.6	PICACHO AREA
20) PV-21	KA1287	1.0	12.7	PLAG.	28.2±3.9	PALO VERDE MOUNTAINS
21) F-8	KA1586	.91	88.0	W/R	30.0±3.0	PALO VERDE MOUNTAINS
22) LC-4	KA1402	.29	10.8	PLAG.	25.6±4.2	LITTLE CHUCKWALLA MOUNTAINS
CAPPING VOLCANIC SEQUENCE (UNIT CA)						
23) CG-32	KA1266	5.2	69.9	PLAG.	18.8±0.2	TABASECO TANKS
24) CG-27	KA1265	1.5	41.0	PLAG.	19.0±0.6	TABASECO TANKS
25) PP-100	KA1407	SEE CROWE (IN PRESS)			13.1±2.5	PICACHO AREA
26) PV-34	KA1289	.73	42.7	PLAG.	56.4±1.6	PALO VERDE MOUNTAINS
27) PV-33	KA1406	.59	30.9	PLAG.	24.5±1.7	PALO VERDE MOUNTAINS
28) F-3	KA1585	.46	89.0	PLAG.	36.4±4.0	PALO VERDE MOUNTAINS
29) AP-10	KA1403	.68	7.1	PLAG.	16.8±4.4	CHUCKWALLA MOUNTAINS
30) HF-1	KA 773	SEE CROWELL (1973)			22.4±2.9	OROCOPIA MOUNTAINS
31) HF-2	KA 778	SEE CROWELL (1973)			20.1±8.9	OROCOPIA MOUNTAINS
32) - -	- -	SEE SPITTLER (1974)			18.6±1.9	OROCOPIA MOUNTAINS
PLUTONIC ROCKS, SOUTHEASTERN CALIFORNIA						
33) CMG1-36	**	8.0	78.4	BIOTITE	23.1±0.7	CENTRAL CHOCOLATE MOUNTAINS
34) CMG1-34	**	8.5	69.3	BIOTITE	22.0±0.7	CENTRAL CHOCOLATE MOUNTAINS
35) CMG1-35		8.5	70.3	BIOTITE	22.1	
	**	8.0	59.7	BIOTITE	22.3±0.7	CENTRAL CHOCOLATE MOUNTAINS
36) CMG1-68	**	8.8	87.6	BIOTITE	23.9±0.7	NORTHERN CHOCOLATE MOUNTAINS
37) CG-R	KA1262	3.0	74.3	SANIDINE	26.0±0.2	NORTHERN CHOCOLATE MOUNTAINS

continued →

OTHER VOLCANIC ROCKS, TRANSVERSE RANGES††

SAMPLE NO.	LAB. NO.	%K	%RAD. AR	MINERAL	AGE (M.Y.)	LOCALITY
38) MC-53	KA1261	4.6	61.8	BIOTITE	15.4±0.2	IGNIMB. CLAST MINT CANYON FM.
39) CALL-LX	KA1288	5.2	81.7	BIOTITE	15.9±0.1	IGNIMB. CLAST CALIENTE FM.
40) VV1-2	KA1408	.59	23.1	PLAG.	24.3±1.6	VASQUEZ VOLCANICS
41) VV1-6	KA1409	.55	50.6	PLAG.	21.5±1.3	VASQUEZ VOLCANICS

* Age determinations by D. Krummenacher, San Diego State University
Decay constants:
$K^{40}/K = 1.19 \times 10^{-4}$
$\lambda\epsilon = 0.585 \times 10^{-10}\,y$
$\lambda\beta = 4.72 \times 10^{-10}\,y$

** Age determination by Fred Miller, U.S. Geological Survey

† Three highly discordant dates from the same volcanic unit. True age probably 17 m.y. (see text).

†† The significance of age dates from the Transverse Ranges will be discussed in a separate publication.

volcanic province to the southern San Andreas fault raises the possibility that clasts derived from these volcanic rocks may be identified in Cenozoic sedimentary units offset along the San Andreas fault system (Crowe, 1973).

In this paper we present the results of regional mapping, petrography, and major-element chemical analyses of the volcanic rocks of southeastern California along with 32 newly obtained K–Ar age determinations (table 1). Our studies of volcanic clasts in sedimentary deposits along the San Andreas fault (and their possible tectonic significance) are still in progress.

CENOZOIC VOLCANIC ROCKS OF SOUTHEASTERN CALIFORNIA

The generalized distribution of Cenozoic volcanic and plutonic rocks within the triangular region of southeastern California bounded by the Orocopia Mountains on the northwest, the Palo Verde-Mule Mountains on the east, and the southeasternmost Chocolate Mountains north of Yuma, Ariz. on the south, is shown on figure 1. The volcanic rocks of this region were studied through a combination of detailed and reconnaissance mapping with emphasis on determination of major stratigraphic relationships at individual volcanic centers. The area of the Chocolate Mountains bounded to the north by Salton Creek and extending south to Mt. Barrow falls within the confines of the Chocolate Mountain Gunnery Range. Ground access was permitted during two 18-day bombing pauses (1974-1975) supplemented by several days of helicopter reconnaissance (1976). Further detailed mapping in the region undoubtedly will refine aspects of the volcanic geology within individual ranges; however, the major stratigraphic relationships should remain unchanged.

Rock nomenclature follows the normative classification of O'Connor (1965) with the dividing line for the classification raised to 15 percent normative quartz. Rocks containing less than 15 percent normative quartz are named following a modified version of Rittman (1953). Where chemical analyses are not available, the rocks are named by comparison with petrographic features of analyzed rocks.

The Salton Sea (Jennings, 1967) and El Centro (Strand, 1962) State Geologic maps, the southern California preliminary fault and geologic map (Jennings, 1973), and the geologic map of Imperial County (Morton, 1976) provided valuable base control for the field studies. Reference to these maps will aid the reader in the following discussions of the regional volcanic stratigraphy.

Tripartite Stratigraphy

The stratigraphic position of major volcanic rock units at separated volcanic centers in southeastern California is broadly similar, and the rocks of each center can be divided into three major sequences (Crowe, 1975). From the base upward, they consist of (fig. 2): (unit A) a basal sequence of basaltic to rhyodacitic lava flows, flow breccia, laharic breccia, and associated plugs. These rocks, referred to as the basal volcanic

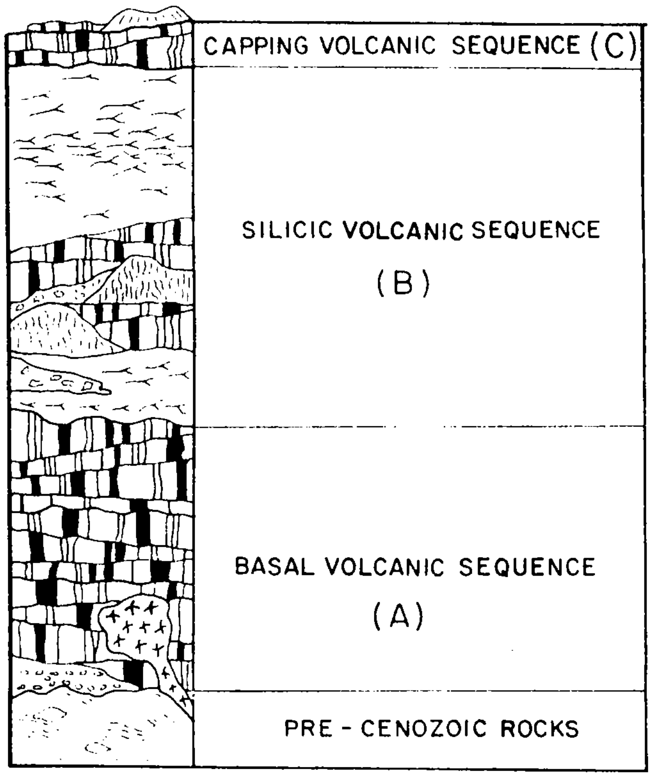


Fig. 2. Generalized stratigraphic column of the regional tripartite volcanic stratigraphy. See text for description of units.

sequence, rest unconformably on pre-Cenozoic basement rocks; locally they overlie and interfinger with fanglomerate. At most localities, the basal volcanic sequence exhibits slight to intense hydrothermal alteration and, with the exception of the Picacho area and the Palo Verde Mountains, is deeply dissected. Within the Chocolate Mountains and possibly the Palo Verde Mountains, the basal volcanic sequence is intruded by cogenetic Cenozoic plutonic rocks (Miller and Morton, 1977; Crowe, 1975; Dillon, ms). (Unit B) The basal volcanic sequence is overlain by rhyodacitic to rhyolitic lava flows, domes, and associated pyroclastic and volcaniclastic rocks referred to as the silicic volcanic sequence. Locally these rocks rest with slight angular discordance on unit A. With the exception of inferred relationships in the southern Chocolate Mountains (Dillon, ms), Cenozoic plutonic rocks in the region do not intrude the silicic volcanic sequence. At several volcanic centers, the upper part of unit B includes major rhyolite ignimbrite sheets. The source areas of the ignimbrites are poorly known with the exception of the Picacho area (Crowe, 1978). Individual ash-flow sheets are remarkably restricted in lateral extent. (Unit C) the youngest volcanic rocks of the region, the capping volcanic sequence, include lava flows ranging in composition from olivine basalt to pyroxene dacite. These volcanic rocks form conspicuous capping lava flows of individual ranges; locally, they are interbedded with and overlie fanglomerate. Based on K–Ar ages, the capping volcanic sequence is divided into two units: capping flows that overlap in age with the silicic volcanic sequence (unit Ca) and capping lava flows that are separated by a distinct age gap from the silicic volcanic sequence (unit Cb). The younger unit occurs at scattered localities in the region and apparently was erupted from vent areas largely unrelated to volcanic centers of units A, B, and Ca.

The recognition of a regional tripartite volcanic stratigraphy does not imply direct correlation of individual volcanic rock units from range to range. Correlation of volcanic rocks deposited within spatially separate volcanic centers generally results in an oversimplified stratigraphic nomenclature that obscures significant regional variations in their ages and eruptive histories. There are significant variations in the *detailed* volcanic stratigraphy of individual volcanic centers resulting from the complex evolutionary processes that produce the spectrum of derivative-magma types. In this paper we emphasize that there are consistent regional *patterns* in the stratigraphic position of major volcanic rock sequences from volcanic center to volcanic center within southeastern California. These patterns form the basis for our tripartite stratigraphic divisions. In the following sections of the paper, we describe the tripartite stratigraphy of volcanic centers in southeastern California. These volcanic centers include the Picacho area (Crowe, 1978), the Quartz Peak-Vinagre Wash area, and the Palo Verde Mountains. Partly overlapping volcanic centers are present in the Chuckwalla-Little Chuckwalla Mountains, and the Black Hills. A continuous series of overlapping volcanic centers probably existed along the length of the Chocolate Mountains. These centers have been largely removed by deep erosion that locally exposed cogenetic plutonic rocks (see figs. 3-6).

Picacho area, southeasternmost Chocolate Mountains.—The Cenozoic volcanic geology of the Picacho area has been described by Crowe (1978). The volcanic rocks range in age from 32 to 25 m.y. and are readily divisible into the tripartite stratigraphic framework. The oldest volcanic rocks consist of trachybasalt to rhyodacite lavas (unit A) that are intruded and overlain by silicic domes and flows, associated volcaniclastic deposits, and a widespread rhyolite ignimbrite (all unit B). The latter unit is locally overlain by pyroxene andesite lava flows dated at 25 m.y. (unit Ca).

Quartz Peak-Vinagre Wash Area.—Cenozoic volcanic rocks exceeding 1000 m in thickness crop out northwest of the Picacho area within the terrane adjoining Quartz Peak and Vinagre Wash and east of Midway Wells (fig. 4). The oldest volcanic rocks consist of lava flows, associated breccia, and plugs that range petrographically from pyroxene andesite to hornblende and pyroxene-bearing dacite or rhyodacite (unit A). The sequence unconformably overlies metamorphosed basement rocks and locally rests upon discontinuous conglomerate and sedimentary breccia derived from the nearby basement rocks. North of the central part of Julian Wash, basal lava flows are interbedded with more than 80 m of volcaniclastic deposits consisting largely of air-fall tuff, reworked pyroclastic deposits, and minor lake deposits. The air-fall deposits are thickest at this locality and are thinner throughout much of the southeastern Chocolate Mountains. The basal volcanic sequence is intruded and overlain by silicic plug-domes, domes, and associated lava flows and volcaniclastic deposits (unit B). This silicic sequence forms a major plug-dome and dome complex north of Gavilan Wash and extends in a broad north-trending band to north of Vinagre Wash (fig. 4). The dome complex is elongate parallel to major north-south trending normal faults suggesting that the faults provided structural control for the emplacement of the volcanic rocks. The dome complex consists of numerous coalesced plug-domes with complexly overlapping extrusive domes, related lava flows, and associated lithic rich, unwelded and welded ignimbrites. The silicic volcanic sequence adjacent to and north of Vinagre Wash has not been studied in detail. The volcanic rocks are similar to the above described deposits, although the stratigraphy is considerably more complicated. Unwelded and welded ignimbrites of sequence B occur at three localities in the Quartz Peak-Vinagre Wash area. A 26 m.y. rhyolite ignimbrite is exposed along the flanks of the Colorado River (ignimbrite of Ferguson Wash; see Crowe, 1978, fig. 3). A separate, crystal-rich rhyolite ignimbrite of unknown age forms Buzzard Peak and extends along the west flank of the small linear range east of Midway Wells (fig. 4). Petrographically similar ignimbrites crop out within small isolated knobs at the northernmost tip of the Quartz Peak-Vinagre Wash area. Capping lava flows of augite-olivine basalt (unit Cb) are interbedded with and overlie volcaniclastic fanglomerate in the western part of the Quartz Peak-Vinagre Wash area (fig. 2). The basalt has been dated at about 13 m.y. (Crowe, 1978). Remnants of cinder-cone deposits preserved beneath lava flows near the north end of Black Mountain represent vent areas for at least part of the lava flows.

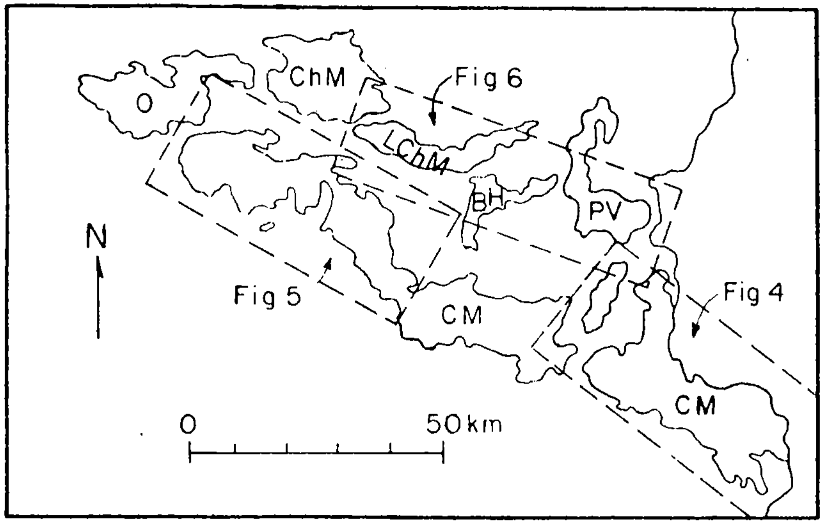


Fig. 3. Index map for figures 4, 5, and 6. CM: Chocolate Mountains; PV: Palo Verde Mountains; BH: Black Hills; LChM: Little Chuckwalla Mountains; ChM: Chuckwalla Mountains; O: Orocopia Mountains.

Southern Chocolate Mountains.—The basement- and volcanic-rock geology of the southern Chocolate Mountains (the area from Mt. Barrow northwest to Salvation Pass) has been mapped and described by Dillon (ms). Volcanic rocks exposed within this area included erosional remnants of intermediate-composition lava flows and breccia (unit A) that overlie basement-bearing breccia and minor air-fall and reworked pyroclastic deposits. Silicic plug-domes, lava flows, and pyroclastic deposits (unit B) intrude and overlie the basal volcanic sequence. These rocks crop out primarily adjacent to and to the south of Mt. Barrow. A large granitic stock (granite of Mt. Barrow) dated at about 21 m.y. (Miller and Morton, 1977) locally intrudes the basal volcanic sequence; the stock in turn is cross cut by a northwest-trending dike swarm that locally intrudes the silicic volcanic sequence. Granitic rocks presumably related to the granite of Mt. Barrow occur throughout the southern Chocolate Mountains (Dillon, ms). The youngest volcanic rocks of this area include capping basalt that is interbedded with fanglomerate approx 6 km southwest of Mt. Barrow. The petrography and major-element chemistry of the volcanic rocks are described by Dillon (ms).

Central Chocolate Mountains. Isolated exposures of dacite lava flows and breccia crop out approx 7 km northeast of Salvation Pass (fig. 5). East and southeast of Surveyors Pass scattered andesitic volcanic rocks form a thin veneer with subdued relief upon the basement rocks.

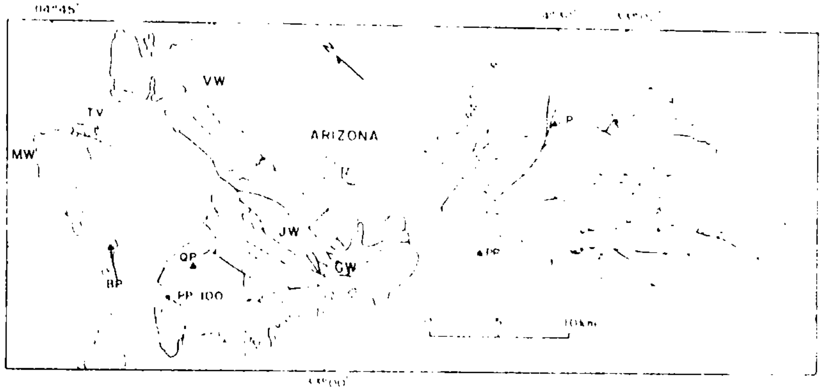


Fig. 4. Generalized geologic map of the Picacho and Quartz Peak-Vinagre Wash areas showing the distribution of Tertiary volcanic rocks (lined pattern) and location of dated sample. PP: Picacho Peak; LP: Little Picacho Peak; GW: Gavilan Wash; JW: Julian Wash; VW: Vinagre Wash; BP: Buzzard Peak; MW: Midway Wells.

Northeast of Surveyors Pass (fig. 5), the volcanic rocks include intermediate-composition lava flows and breccia (unit A) that rest on laminated gneiss and foliated granitic rocks. The flows and the basement rocks are intruded by porphyritic quartz-sanidine granite dikes that may be shallowly emplaced offshoots of granitic rocks exposed to the west (fig. 5). This basal volcanic sequence is locally overlain by laharic breccias up to 40 m thick that contain clasts of the underlying flow rocks, flow-banded silicic clasts not locally present, and abundant angular clasts of a rhyolite ignimbrite, all in a tuff matrix. To the south, the laharic breccia pinches out onto deposits of unwelded and welded rhyolite ash-flow deposits approx 30 m thick (unit B).

Volcanic rocks of Iris Pass form the thickest deposits of the central and northern Chocolate Mountains (fig. 5). Basal volcanic rocks consist of discontinuously exposed lava flows and breccia ranging in composition from porphyritic pyroxene andesite to hornblende rhyodacite (unit A) that form the roof rocks of a brecciated porphyritic granitic stock. The stock intrudes the basal volcanic sequence, contains isolated pods of gneiss, and intrudes Cenozoic (?) plutonic rocks (granodioritic to quartz monzonitic) exposed in the upper part of the Iris Pass area (fig. 5). The granite stock and basal volcanic rocks are overlain with slight angular discordance by a complex sequence of silicic volcanic rocks including pyroclastic deposits of air-fall and ash-flow origin surrounding isolated domes and plug domes of porphyritic rhyolite and locally thick silicic lava flows (unit B). Plagioclase separated from a perlitic vitrophyre at the base of a rhyolite flow yielded a date of 23.5 ± 1.1 m.y. (CG-57; see table 1). The Iris Pass area is capped by unwelded and welded rhyolite ignimbrite (unit B) that dips moderately to the northeast and is cross cut by north-south trending normal faults. The ignimbrite forms a compound single cooling unit with a minimum exposed thickness of 100 m. It is exposed in the Iris Pass area, along the southeastern margin of Surveyors Pass, and significantly is not present in the ranges across the alluvial valley east of the Chocolate Mountains. Samples of the ignimbrite obtained at two separate localities in the Iris Pass area yielded ages of 23.3 ± 0.7 m.y. (CG-55) and 23.7 ± 0.3 m.y. (CG-612).

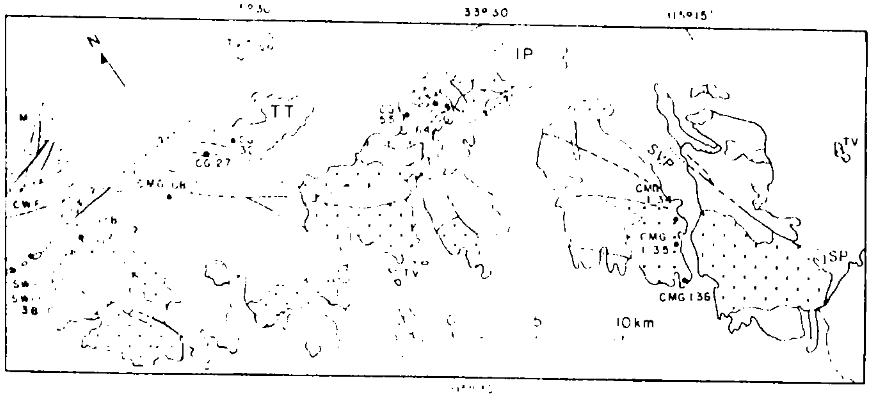


Fig. 5. Generalized geologic map of the northern and central Chocolate Mountains showing the description of Tertiary volcanic (lined pattern) and plutonic (stippled pattern) rocks and locations of dated samples. Tertiary plutonic rocks have not been mapped in the northeastern part of the northern Chocolate Mountains. SP: Salvation Pass; SVP: Surveyors Pass; IP: Iris Pass area; TT: Tabaseco Tanks area; OM: Orocopia Mountains; CWF: Clements Well fault; SCF: Salton Creek fault.

Scattered volcanic rocks crop out within alluvial deposits in the western part of the central Chocolate Mountains. They include a northwestward aligned chain of aphyric rhyolite domes and minor pyroxene-bearing flow rocks both present several kilometers northwest of Marcella Mine (fig. 5).

Northern Chocolate Mountains.—In the north-central Chocolate Mountains scattered volcanic rocks locally rest on pre-Cenozoic (?) basement rocks and are intruded by plutonic and associated dike and plug rocks (fig. 5). The volcanic rocks include hydrothermally altered andesitic lava flows and breccia (unit A) that form the roof of the plutons. Isolated exposures of altered hornblende rhyodacite and minor pyroclastic rocks (unit B) are present several kilometers to the south (fig. 5).

In the northeastern Chocolate Mountains, at Tabaseco Tanks, Cenozoic volcanic rocks form a major rhyolite dome field (unit Cb). Individual domes are elongate in an east-west direction, and the largest dome is approx 2 km long and 0.5 km wide. The domes intrude cogenetic flank deposits of pyroclastic rocks, breccia tongues shed from the domes, and several small rhyolite flows (?). Dome contacts are steep, and interior flow banding strikes generally east-west with near vertical dips. Petrographically there are two varieties of dome rocks: rhyolite containing scattered phenocrysts and microphenocrysts of plagioclase, sanidine, hornblende, biotite with minor hypersthene and augite, and porphyritic rhyolite with abundant phenocrysts of sanidine, minor plagioclase, and altered ferromagnesium minerals. Plagioclase separated from the perlitic margin of a dome in the western part of the field was dated at 18.8 ± 0.2 m.y. (CG-32). The rhyolite domes are unconformably overlain by southwest-dipping volcaniclastic conglomerate that is interbedded with a thin lava flow of platy augite–hypersthene dacite (unit Cb). The dacite yielded a K–Ar age of 19.0 ± 0.6 m.y. (CG-27).

A linear series of deeply dissected domes crops out through alluvial deposits along Salton Creek between the Orocopia and northern Chocolate Mountains (fig. 5). There are nine separate domes, although some may be continuous in subsurface. Two of the domes are hornblende-two pyroxene rhyodacite, the remainder are sanidine rhyolite. K–Ar age determinations of samples collected from separate domes yielded surprisingly old dates of 33.0 ± 1.0 m.y. (SW-1) and 27.3 ± 0.4 m.y. (SW1-3B). These are significantly older than K–Ar ages obtained for silicic volcanic rocks in the northwest part of the region, and for this reason, the dates may be anomalous.

Plutonic rocks of the northern and central Chocolate Mountains.—Plutonic rocks, in part contemporaneous with the volcanic rocks described above, crop out throughout the western and central part of the central and northern Chocolate Mountains. They form complex stocks ranging from granodiorite or quartz monzonite to porphyritic granite and have not been studied in detail. In the central Chocolate Mountains, two intrusive phases have tentatively been recognized. These include porphyritic granite that intrudes slightly more mafic granitic rocks which are exposed only in the eastern part of the Chocolate Mountains. Samples collected from the younger plutonic rocks exposed along Surveyors Pass yielded ages of approx 22 to 23 m.y. (CMG1-34 to 1-36). In the northern Chocolate Mountains two, and possibly three, separate plutonic phases are present. In the central part of the area, roof rocks (largely volcanic) are riddled by numerous dikes and sills that emanate from the subjacent plutons. Sanidine separated from a sill derived from a granite stock in the north-central Chocolate Mountains yielded a date of 26.0 ± 0.2 m.y. (CG-B). In the largely unmapped basement terrane of the northeastern Chocolate Mountains, biotite separated from a plutonic rock that intrudes laminated gneiss was dated at 23.9 ± 0.7 m.y. (CMG1-68).

Chuckwalla Mountains.—Volcanic rocks of the southwestern Chuckwalla Mountains are similar to and may originally have been continuous with volcanic rocks of the Little Chuckwalla Mountains (fig. 6). Near vertical northwest-trending faults that in part bound the volcanic field of the former area cut both the volcanic rocks as well as young alluvial deposits (see Jennings, 1973). Basal volcanic rocks of the Chuckwalla Mountains include porphyritic olivine and pyroxene-bearing lava flows and breccia (unit A); an andesite from the base of the section (AP-2) was dated at 25.7 ± 1.3 m.y. Capping lava flows of porphyritic augite–olivine andesite (unit Cb) dated at 16.8 ± 4.1 m.y. (AP-10) unconformably overlie the basal volcanic sequence. Several kilometers south of Chuckwalla Springs (fig. 6), the basal volcanic sequence is intruded and overlain by sanidine rhyolite plug-domes (unit B) that are not in contact with the capping andesite. To the south, at Indian Well (fig. 6), isolated hydrothermally altered rhyolite domes crop out within alluvium (unit B).

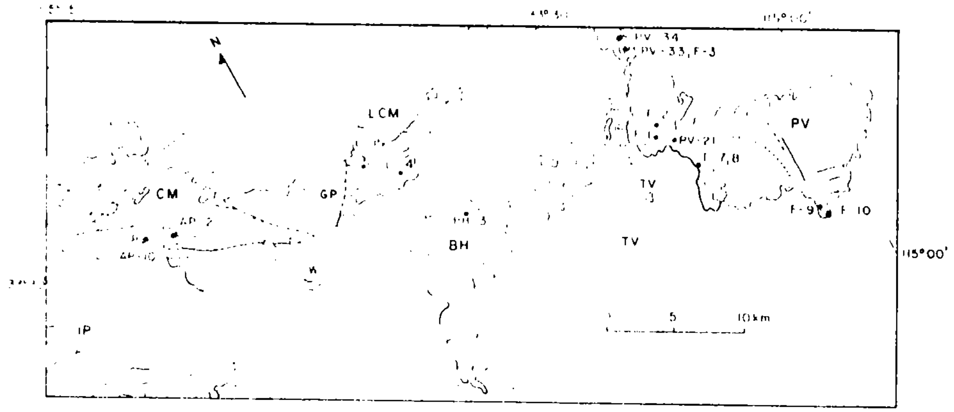


Fig. 6. Generalized geologic map of the Chuckwalla, Little Chuckwalla, Palo Verde Mountains, and the Black Hills showing the distribution of Tertiary volcanic rocks and the locations of dated samples. PV: Palo Verde Mountains; BH: Black Hills; LCM: Little Chuckwalla Mountains; CM: Chuckwalla Mountains; IW: Indian Wells; IP: Iris Pass area; GP: Graham Pass area.

Little Chuckwalla Mountains.—Scattered volcanic rocks crop out in Graham Pass southeast of a northeast-trending fault and are probably eroded remnants of a thick south southeast dipping volcanic pile exposed to the east (fig. 6). Several kilometers east of Graham Pass the basal volcanic sequence rests on granitic basement rocks and includes lava flows and breccia ranging in composition from olivine basalt to pyroxene rhyodacite. The basal volcanic sequence (unit B) of the Chuckwalla-Little Chuckwalla Mountains is unusual in several respects in comparison to other volcanic rocks of the region. It is only mildly affected by secondary alteration, olivine is both a major phenocryst phase and present in the groundmass throughout much of the sequence, and volumetrically, the volcanic rocks consist predominantly of andesite. A porphyritic two-pyroxene andesite (LC-15) from the base of the volcanic section yielded a K–Ar age of 25.5 ± 0.2 m.y. and overlaps in analytical uncertainty with the dated sample from the base of the volcanic sequence in the Chuckwalla Mountains. The basal volcanic sequence is overlain with slight angular discordance by volcanic bearing conglomerate and is interbedded with lava flows of pyroxene andesite (unit Ca) dated at 25.6 ± 4.2 m.y. (LC-4). The volcanic conglomerate locally laps onto a large silicic dome. The dome ranges petrographically from porphyritic pyroxene–hornblende rhyodacite present in the lowermost exposure of the dome, to flow-banded, aphyric rhyolite in the structurally highest part. Silicic dikes cut the basal volcanic sequence in the western Little Chuckwalla Mountains and are overlain by conglomerate. The dike rocks include aphyric rhyolite and porphyritic pyroxene–hornblende–biotite rhyodacite; both types are similar petrographically to the silicic dome.

Little Mule Mountains Black Hills. Southeast and south of the Little Chuckwalla Mountains, volcanic rocks are exposed in the Little Mule Mountains and Black Hills (fig. 6). In the Little Mule Mountains, the basal volcanic sequence consists of lava flows, flow breccia, and minor laharic breccia that rest unconformably on gneissic and granitic rocks exposed only in the southernmost tip of the range. The flows are strongly altered and consist largely of porphyritic pyroxene-bearing dacite with hornblende–pyroxene-biotite rhyodacite present in the upper part of the sequence (unit A). This sequence is overlain by remarkably widespread rhyolite lava flows (unit B). In the southern part of the Little Mule Mountains, the rhyolite flows are relatively thin. They thicken to the northeast, where the flows overlie pyroclastic deposits largely of air-fall origin. In the westernmost Black Hills, a large and complex perlitic to felsophyric plug-dome intrudes the basal and silicic volcanic sequences and is probably a major feeder for the upper silicic lava flows. A perlite from the margin of the plug-dome yielded an age of 22.1 ± 1.3 m.y. (BH-3). East of the plug-dome, tilted fault (?) blocks expose rocks of the basal volcanic sequence (unit A) and overlying air-fall deposits and rhyolite lava flows (unit B). In the eastern part of the Black Hills, the basal volcanic sequence is overlain by unwelded and welded rhyolite ignimbrite (unit B) that comprises two-cooling units (Tarshis, 1973). These deposits are not in contact with the rhyolite lava flows to the east. The upper cooling unit forms a major ignimbrite sheet in the eastern Black Hills and is locally overlain by volcaniclastic conglomerate. The ignimbrite has been dated at about 21 m.y. (Andrew Tarshis, personal commun., 1975).

Palo Verde Mountains.—The Palo Verde Mountains are formed of a very thick accumulation of volcanic and volcaniclastic rocks that rest unconformably on basement rocks exposed only in the southwestern part of the range (fig. 6). The basal volcanic sequence is composed of lava flows, breccia, and minor pyroclastic deposits. Flow rocks are porphyritic, highly altered, and span a compositional range from andesite to rhyodacite. Adjacent to and south of Palo Verde Peak (fig. 6), rocks of the basal volcanic sequence strike northward with moderate (15° to 25°) easterly dips. West of Palo Verde Peak, the rocks bend to the northwest and west with northeast and north dips. A major dike swarm cuts the basal volcanic sequence and parallels this arcuate structure as do linear hornblende rhyodacite plugs one of which yielded a K–Ar age of 34.7 ± 1.3 m.y. (F-9). In the southwestern part of the range, the basal volcanic sequence is intruded by a hypabysal plug of pyroxene dacite. Local dikes emanating from the plug are similar petrographically to dike rocks of the arcuate dike swarm. The arcuate strikes of the volcanic rocks and the arcuate trend of intrusive rocks suggest the presence of an unexposed plutonic body concealed beneath the thick volcanic cover such that the arcuate structural patterns are inferred to reflect broad magmatic doming above the plutonic body. Major vertical uplift along arcuate faults is suggested by the repetition of a distinctive 30 m section of air-fall and reworked pyroclastic deposits in the central part of the range; if there is no repetition by faulting the basal volcanic sequence has a total thickness in excess of several kilometers. Projected closure of the curvature of the arcuate structure produces a dome with a diameter of over 11 km that presumably reflects the dimensions of the inferred plutonic body at depth. The basal volcanic sequence is intruded by biotite–hornblende rhyodacite plug domes (unit B) near Thumb Peak that are elongate in a northwest direction (fig. 6). A perlite collected from the margin of a plug-dome near Thumb Peak yielded an age of 25.2 ± 2.5 m.y. (F-2). In the southwestern part of the Palo Verde Mountains, the silicic plug-domes are locally overlain by a biotite–sanidine rhyolite welded ignimbrite (unit B). The ignimbrite, dated at 25.6 ± 1.0 m.y. (F-7) and 27.9 ± 9 m.y. (F-1), occurs north of Thumb Peak, obtains maximum thickness in the southwestern part of the range, and pinches out beneath the central Palo Verde Mountains. It is petrographically similar to the ignimbrite of the Black Hills but is clearly older. The absence of the two separate ignimbrite sheets within the closely adjacent ranges (Black Hills and Palo Verde Mountains) strongly suggests the presence of a major (and now buried?) structural feature that topographically separated the ranges during emplacement of the ignimbrites (fig. 6). In the central Palo Verde Mountains, the older ignimbrite is overlain by capping lava flows of olivine andesite (unit Ca) dated at 30.0 ± 3.0 m.y. (F-8; whole rock) and 28.2 ± 3.9 m.y. (PV-21; plagioclase). In the northern part of the range, the basal volcanic sequence is overlain by volcaniclastic conglomerate in turn overlain by platy lava flows and breccia of augite–hypersthene andesite. The andesite has yielded three highly discordant dates of 56.4 ± 1.6 m.y. (PV-31), 21.5 ± 1.7 m.y. (PV-33), and 36.4 ± 4.0 m.y. (F-3). Fugro Inc. has obtained two concordant dates of about 17 m.y. from the andesite (Kent Murray, personal commun., 1976; K–Ar ages determined by Geochron). The older ages are inconsistent with age and stratigraphic determinations elsewhere within the Palo Verde Mountains. The 17 m.y. dates are probably the true age of the andesite. This age corresponds to the age of the younger unit of the capping volcanic sequence in the region. In the southeastern part of the Palo Verde Mountains, a thin rhyolite ignimbrite overlies the basal volcanic sequence and yielded an age of 23.1 ± 0.9 m.y. (F-10). It is slightly younger than and is probably unrelated to the ignimbrite of the southwestern Palo Verde Mountains.

MAJOR-ELEMENT CHEMISTRY

Representative major-element chemical analyses and norms for volcanic rocks from individual volcanic fields of southeastern California are presented in table 2. A total of 70 analyses were completed (XRF and atomic absorption techniques); a list of the analyses with sample locations and brief petrographic descriptions are available from the authors upon request. The chemical data are presented to document major-element chemical characteristics of the individual volcanic fields and to provide a comparative basis for examination of regional chemical patterns. In general the volcanic rocks are slightly to moderately altered and constitute remnants of formerly more extensive volcanic fields. Consequently there is limited control in some areas on determination of the original distribution and volumes of the volcanic rocks. Relative volumes of rocks of contrasting compositions can only be approximately calculated. For such a large area, the number of analyses is insufficient to evaluate intra-suite chemical variation. The data are presented primarily for classification purposes.

Basal and silicic volcanic sequences.—Based on field study and isotopic dating, rocks of the basal and silicic volcanic sequence are distinct stratigraphic units. However there is complete overlap in whole rock major element chemistry for rocks of the two units. They differ only in the relative volumes of rock types. An average composition of the basal volcanic sequence weighted according to estimated original rock volumes

TABLE 2

Chemical analyses and norms of representative volcanic and plutonic rocks, Southeastern California

Chemical Analyses Calculated Water Free

	Quartz Peak - Vinagre Wash Area			Northern and Central Chocolate Mtns.					Chuckwalla - Little Chuckwalla Mtns.				Palo Verde Mtns.		
Strat. Unit	A	B	B	A	B	B	Cb	A	A	A	Ca	Cb	B	Ca	Cb
Field No.	6B-27	6B-30	6B-28	CG-51	CG-57	CG-69	CG-42A	CG-10	AP-2	LC-9	BH-24	AP-10x	PV-29	PV-21	PV-34
SiO_2	63.4	68.6	72.0	68.4	72.8	73.8	59.1	74.3	57.7	57.6	57.1	56.5	70.0	56.0	60.9
Al_2O_3	18.7	14.9	14.5	16.1	14.5	14.1	16.8	14.5	16.1	17.6	16.8	17.5	15.3	16.6	17.4
++FeO	2.7	3.9	2.2	3.7	2.2	1.6	7.9	1.6	7.6	7.5	6.5	8.6	2.8	8.8	6.4
MgO	2.7	1.9	0.3	1.0	0.5	0.2	3.1	0.3	5.3	3.6	4.3	4.3	0.3	5.9	2.9
CaO	4.1	3.3	1.9	2.5	1.6	1.1	6.1	0.5	6.6	7.6	6.4	6.7	1.2	7.3	5.9
Na_2O	4.0	3.8	3.2	3.6	3.4	3.9	3.4	3.6	2.7	2.9	4.1	2.6	4.9	2.7	3.2
K_2O	3.8	3.0	5.8	4.1	4.7	4.9	2.3	5.0	2.6	1.8	3.0	2.1	4.9	1.4	1.9
TiO_2	0.5	0.5	0.1	0.5	0.2	0.2	1.3	0.1	1.4	1.3	1.7	1.7	0.5	1.1	1.3
							Norms (CIPW)								
Q	11.0	23.2	24.9	22.7	28.2	27.4	11.2	30.1	8.5	11.0	2.8	9.7	18.3	8.5	15.9
or	22.2	18.1	34.5	24.8	28.2	29.0	13.6	29.7	15.5	10.9	17.6	12.6	28.7	8.1	11.1
ab	35.5	34.4	29.0	32.6	31.1	35.2	30.7	32.9	24.4	26.0	36.6	23.3	43.6	24.8	28.8
an	20.2	14.6	8.2	12.3	8.1	5.7	24.3	2.6	24.1	30.1	18.4	30.6	5.6	29.1	28.1
C	0.6	0.0	0.0	1.4	0.7	0.4	0.0	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
di	0.0	1.7	1.1	0.0	0.0	0.0	5.2	0.0	6.9	6.5	10.6	2.4	0.5	5.8	1.2
hy	8.8	5.2	1.0	3.6	2.2	1.2	10.4	1.2	16.5	11.0	9.4	16.6	1.3	18.9	10.6
mt	1.0	2.2	1.2	2.1	1.2	0.9	2.9	0.9	2.2	2.8	2.4	2.4	1.5	3.3	2.4
il	0.7	0.6	0.2	0.7	0.3	0.2	1.8	0.1	1.9	1.8	2.3	2.4	0.6	1.6	1.9

GB-27	Augite–hypersthene–hornblende dacite. Collected from lava flow sequence north of Vinagre Wash.
GB-30	Pyroxene (altered)–hornblende rhyodacite vitrophyre. Collected from thick flow north of Vinagre Wash.
GB-28	Biotite–sanidine rhyolite welded ignimbrite; zone of partial welding: zone of complete devitrification. Collected from capping ignimbrite east of Midway Wells.
CG-51	Altered porphyritic pyroxene dacite(?). Collected from basal lava flow sequence, Iris Pass.
CG-57	Porphyritic augite–hypersthene–hornblende quartz latite vitrophyre. Collected from glassy margin of large dome, central Iris Pass.
CG-69	Biotite–sanidine rhyolite welded ignimbrite; zone of partial welding; zone of partial devitrification. Collected from isolated exposures, eastern Iris Pass.
CG-42A	Augite–olivine andesite. Collected from isolated exposure between Chuckwalla and northern Chocolate Mountains.
CG-10	Fine-grained, sanidine-bearing granite. Collected near roof of stock, northern Chocolate Mountains.
AP-2	Fine-grained, pyroxene–olivine andesite. Collected near base of lava flow sequence, Chuckwalla Mountains.
LC-9	Fine-grained, augite–olivine andesite. Collected in central part of lava flow sequence, Little Chuckwalla Mountains.
BH-24	Porphyritic hypersthene–augite andesite. Collected from capping lava flow interbedded with fanglomerate, Little Chuckwalla Mountains.
AP-10x	Porphyritic hypersthene–augite–olivine andesite. Collected from capping lava flows, Chuckwalla Mountains.
PV-29	Biotite–sanidine rhyolite welded ignimbrite; zone of partial welding; zone of partial devitrification. Collected from ignimbrite sheet, southwestern Palo Verde Mountains.
PV-21	Augite–olivine andesite. Collected from capping lava flow sequence, central Palo Verde Mountains.
PV-34	Augite–hypersthene andesite. Collected from capping lava flow, northern Palo Verde Mountains.

would roughly correspond to dacite; that of the silicic volcanic sequence to quartz latite (following the classification of O'Connor, 1965). A significant feature of the volcanic rocks of southeastern California with the exception of the Chuckwalla-Little Chuckwalla volcanic rocks, as previously noted, is the volumetric subordinance of andesite (see also Crowe, 1978).

Selected chemical parameters for the basal and silicic volcanic sequences are listed in table 3. The volcanic rocks have SiO_2 contents that range from 51 to 76 percent (all oxide abundances listed are calculated water free) with the bulk of the analyses bracketed by the range 65 to 72 percent SiO_2. Al_2O_3 ranges from 12.04 to 18.71; the majority of samples have Al_2O_3 contents of 14 to 17 percent. Alkali-lime indices for the sequences, with the exception of the Black Hills, are 60 and 61 (table 3), corresponding to the calc–alkalic and boundary between the calc–alkalic and calcic rock series of Peacock (1931). The basal and silicic volcanic sequences show no iron-enrichment relative to magnesium through the range of SiO_2 contents. All analyzed rocks fall into the subalkaline field of Irvine and Baragar (1971; fig. 7) and are here classified as broadly calc–alkaline in character. K_2O contents corresponding to 57.5 and 65 percent SiO_2 for the volcanic fields are shown in table 3; they are typical of continental-margin volcanic rocks (Dickinson, 1975). A distinctive characteristic of the volcanic sequences, in comparison to volcanic suites of the Cascade range, for example, is the slight excess of K_2O over Na_2O. Averaged $K_2O/Na_2O + K_2O$ for individual volcanic centers of the region ranges from 0.46 to 0.54 (table 3). The lowest ratio for the region is that of the Little Chuckwalla-Chuckwalla suite which again is distinctive by the predominance of andesite. The basal and silicic volcanic sequences are similar with respect to total alkalies versus silica to widespread mid-Cenozoic volcanic suites of the Basin and Range province (fig. 7).

TABLE 3
Selected chemical parameters: sequences A and B

	Picacho* Area	Gold Basin	Palo Verde	Chuckwalla Little Chuckwalla	Northern & Central Chocolate Mts.
Alkali-lime index	61	61	61	60	60
K_2O at 57.5 SiO_2	2.3	1.5	1.7	2.3	2.4
K_2O at 65. SiO_2	2.3	2.6	2.5	3.6	3.3
Average $\frac{K_2O}{Na_2O+K_2O}$	.54	.50	.50	46	.54
Number of Analyses	44	11	12	13	32

* See Crowe, in press

Capping volcanic sequence.—Rocks of the capping volcanic sequence are divided into two suites on the basis of K–Ar ages. They overlap completely and are indistinguishable with regard to petrography and major-element chemistry (table 2). The lavas have SiO_2 contents that range from 52 to 65 percent; all are quartz normative with the exception of the basalt of Black Mountain (hypersthene normative). The rocks are relatively rich in Al_2O_3 (16.40 to 17.40 percent) with slightly high TiO_2. They show no evidence of iron enrichment relative to magnesium, and total iron contents (FeO) for the basalt and olivine andesites of the region are moderate. Total alkali values are also moderate, and all analyses plot in the sub-alkaline field of Irvine and Baragar (1971). A pyroxene andesite from the eastern Little Chuckwalla Mountains plots, however, on the boundary of the extended alkali field of MacDonald and Katsura (1964). Rocks of the capping volcanic sequence are perhaps most distinctive by their generally high Al_2O_3 contents. They are notably less alkalic than alkali–olivine basalts of the Basin and Range province (Leeman and Rogers, 1970) and are somewhat similar to but lower in Al_2O_3 than capping volcanic rocks of west-central Nevada (Vitaliano, 1970). The capping volcanic sequence is distinguishable chemically from the basal and silicic volcanic sequences by the relative abundances of Na_2O and K_2O. $K_2O/Na_2O + K_2O$ ranges from 0.24 to 0.47 and averages 0.35 for the capping volcanic sequence, whereas the basal and silicic volcanic sequences average 0.51 (see table 3).

REGIONAL CONSIDERATIONS

Space-time patterns of Cenozoic igneous activity in the western United States have been related in various ways to changes in plate configurations along the western continental margin (for example, Mc-

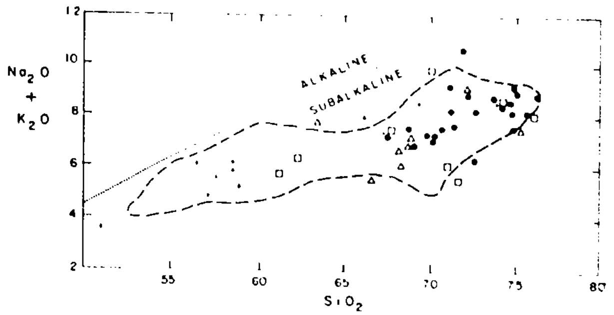


Fig. 7. Total alkalis versus silica diagram. Crosses: Chuckwalla-Little Chuckwalla Mountains; filled circles: Northern and central Chocolate Mountains; open squares: Palo Verde Mountains; open circles: Black Hills; open triangles: Quartz Peak-Vinagre Wash area. Dotted line separates alkaline and subalkaline field (Irvine and Baragar, 1971). Dashed line encloses field of representative Cenozoic calc-alkaline volcanic suites in the basin-range province (from Crowe, 1978).

Kee, 1971; Lipman, Prostka, and Christiansen, 1971, 1972; Christiansen and Lipman, 1972; Noble, 1972). The detailed model of Cenozoic volcanism of Lipman, Prostka, and Christiansen (1971) has received continued support as more data have become available (for example, Armstrong and Higgins, 1973; McKee and Silberman, 1975; Snyder, Dickinson, and Silberman, 1976). The model has provided a basis for comparison of volcanic and tectonic patterns within individual areas of the western United States (Scholtz, Barazangi, and Sbar, 1971; Elston and others, 1973). In brief, the major aspects of the model of Lipman, Prostka, and Christiansen (1971) are:

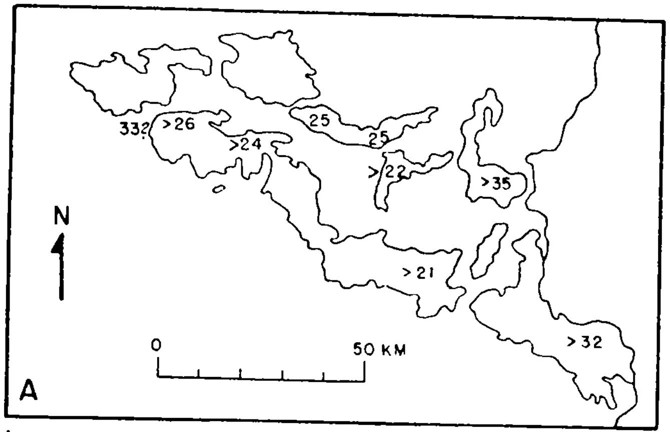
1. Cenozoic volcanism throughout much of the western United States during early and middle Cenozoic time was broadly andesitic in character (andesite–rhyolite association), although there are considerable regional variations in age and chemical compositions of the rocks. In general their known characteristics suggest that they represent continental-arc assemblages related to an east-dipping subduction system of probable complex geometry.

2. The andesitic association was replaced in mid-to-late Cenozoic time by a fundamentally basaltic association, whose age closely coincided with the onset of regional extensional faulting. Variations in the timing and the spatial distribution of the transition to fundamentally basaltic volcanism suggest a genetic relationship with triple-point migration along the continental margin and development of the San Andreas system.

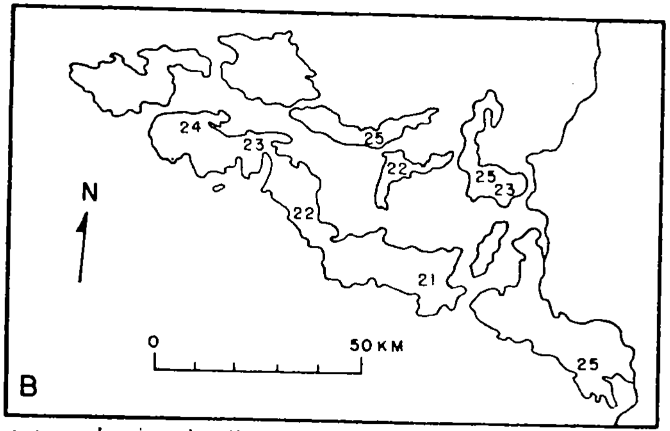
If we examine regional volcanic patterns of southeastern California within the framework of the Lipman and others' model, the rocks of southeastern California are critical for two reasons. First, they lie adjacent to the complex tectonic region where faults of the San Andreas system merge with the Salton Trough-Gulf of California system, and second, we have obtained field, chemical, and age data for a large area in which no previous data were available.

Inception of volcanism.—Cenozoic volcanism in southeastern California began in mid-Oligocene time following a pronounced period of early Cenozoic magmatic quiescence (fig. 8A). The youngest known igneous rocks of the region that predate the volcanic suites include scattered plutonic rocks that yield K–Ar ages of 50 to 70 m.y. (many of the dated rocks are probably significantly older; see Armstrong and Suppe, 1973, p. 134) and metavolcanic and metaplutonic rocks of the southeasternmost Chocolate Mountains inferred to be of late Cretaceous or early Cenozoic (?) age (Haxel, ms). An early Cenozoic hiatus in volcanic activity has been recognized in the Great Basin south of latitude 42°N (McKee and Silberman, 1975) and in part of the southern basin-range province (Damon and Mauger, 1966). Cross (1973), Cross and Pilger (1974), and Snyder, Dickinson, and Silberman (1976) have suggested that the absence of early Cenozoic volcanism may reflect initiation of a proto-San Andreas fault system in coastal California. However, presently available evidence suggests a post-middle Miocene age of initia-

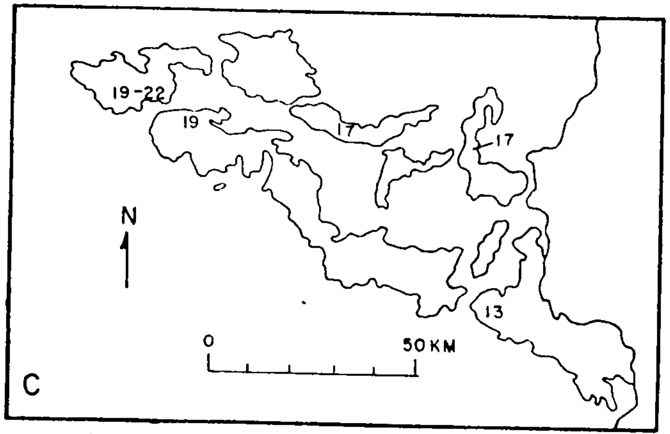
Fig. 8



A. Index map showing distribution of K-Ar ages documenting the age of inception of volcanism in southeastern California. Ages shown are the oldest K-Ar ages for individual volcanic centers; the true age of inception of volcanism is older by a small but unknown amount.



B. Index map showing the distribution of the youngest K-Ar ages for sequences A, B, and Ca. These ages correspond to but are slightly younger than the probable age of termination of subduction in coastal southern California.



C. Index map showing the distribution of K-Ar ages for the younger unit of the capping volcanic sequence (sequence Cb).

tion of movement for the San Andreas system south of the Transverse Range (Crowell, 1973, 1975; Ehlig, Ehlert, and Crowe, 1975). A proto-San Andreas fault system to the west in southern California or the adjacent borderland (for example, Suppe, 1970; Crowell, 1975; Howell and others, 1974) may have been active during the period represented by the volcanic hiatus. Alternatively, Snyder, Dickinson, and Silberman (1976) suggest that the volcanic hiatus may be a reflection of subsurface geometric complexities in the subducted plate.

Examination of figure 8A shows that there are no obvious regional trends in the age of inception of volcanism in southeastern California. Most of the dates shown, however, are minimum ages, and the true age of inception of volcanism is older by some unknown value. This is due in part to the difficulty in obtaining datable samples from the basal volcanic sequence. As shown by figure 8B and table 1, the age range of the basal and silicic volcanic sequences of the area overlap with know ages of Cenozoic volcanism in central and southeast Arizona (Sheridan, Stuckless, and Fodor, 1970; Damon and Mauger, 1966) and southwestern New Mexico (Elston and others, 1973). The volcanic rocks of this broad region correspond to the Arizona locus of Snyder, Dickinson, and Silberman (1976).

North of southeastern California, ages of volcanic rocks from the Turtle, Nopah, and Wipple Mountains are somewhat younger than the volcanic rocks of southeastern California (AEC project no. 486, 1974). Anderson and others (1972) and Thorson (ms) have described still younger volcanic rocks within the Lake Mead area. Damon (1976) has noted a tendency for a northwest decrease in the age of ash-flow deposits in the southern basin-range province. The significance of these trends remains to be investigated by further field study and dating, particularly in southwestern Arizona.

The basal and silicic volcanic sequences of southeastern California are similar in age and major-element chemistry to the early and middle Cenozoic calc–alkaline suites of Lipman, Prostka, and Christiansen (1972). Thus, following the model of Lipman, Prostka, and Christiansen (1972), the former rocks could reasonably be attributed to an early Cenozoic subduction system off the coast of the western United States. Averaged K_2O contents at 57.5 percent SiO_2 for the calc–alkaline suites of southeastern California yield a calculated depth to the top of an inferred subduction zone of approx 190 km using the K_2O curves of Dickinson (1975). This depth calculation is compatible with depth contours of the western decoupled subduction zone of Lipman, Prostka, and Christiansen (1972, fig. 9) assuming a slight southeastward bend of the projection of the 200 km contour in southern California. The data are equally compatible with an alternate depth contour diagram based on K_2O contents of post-40 m.y. volcanic rocks of the western United States (Elston, 1976). This alternate plot requires a single subduction zone and emphasizes the anomalous character of the Colorado Plateau. It should be noted, however, that while not a necessary constraint for the volcanic rocks of southeastern California, neither model explains the great distance of some of the easternmost volcanic suites (San Juan Province, Mogollon-Datil Province) from the inferred coastal-trench system (Gilluly, 1971) nor the anomalous depths to the top of the subduction zone suggested by K_2O contents.

Plutonic rocks.—Dated plutonic rocks of the Chocolate Mountains overlap in age with those of the silicic volcanic sequence despite the regional stratigraphic disconformity between the rocks (fig. 2). Several possibilities are suggested to explain this discrepancy. Despite the shallow depth of emplacement of the plutonic rocks (intruding volcanic cover), regional thermal effects in an area of prolonged active plutonism and volcanism may have been pronounced, so that the plutonic dates are minimum ages. Moreover, post-plutonic silicic volcanism may have maintained regional thermal gradients above the closure temperatures of dated minerals.

Plutonic rocks of known Cenozoic age within southeastern California are restricted to the Chocolate Mountains (fig. 4). This distribution clearly is an effect of post-volcanic erosion, and it is likely that Cenozoic plutonic rocks lie concealed at depth beneath many of the less dissected volcanic fields. For example, volcanic rocks of the central and northern Chocolate Mountains are exposed primarily along the eastern flanks of the range, whereas plutonic rocks are exposed in the west. The distribution is suggestive of uplift accompanied by eastward titling of the range with resultant deeper erosion in the west (Murray and Crowe, 1976). The arcuate structure and associated intrusive rocks of the Palo Verde Mountains may represent broad doming and roof intrusions above an underlying plutonic body.

Capping volcanic sequence.—Based on stratigraphic position, the capping-volcanic sequence appears to correspond to the fundamentally basaltic association of Christiansen and Lipman (1972). However, the sequence has been subdivided into two suites that overlap completely in chemical composition but have distinctly differing ages. The older suite (unit Ca) overlaps in age with but is volumetrically subordinate to the silicic volcanic sequence (table 1). It represents an episode of predominantly mafic volcanism during the waning stages of calc–alkaline activity. A distinct stage of mafic volcanism that precedes, accompanies, and follows intermediate-to-silicate composition volcanism is recognizable at many volcanic centers of varying ages throughout the western United States. For example, in the Mogollon-Datil volcanic province of southwestern New Mexico, a basaltic andesite suite is associated with and postdates calc–alkalic and alkalic rhyolite suites (Elston and others, 1976, p. 5). Eichelberger and Gooley (1977) suggest that encroachment of mafic volcanism onto central silicic complexes during the waning stages of volcanism is a common feature of igneous complexes formed by mixing of basaltic and rhyolitic magmas.

The younger unit of the capping volcanic sequence (unit Cb) crops out along the flanks of and separate from centers of older calc–alkalic activity. Moreover the former lavas are of relatively small volume and are separated by a notable time interval from the older suites. The capping sequence represents a separate phase of mafic and intermediate volcanism and for this reason corresponds to the fundamentally basaltic association. Note however, that the rock compositions of the younger unit (calc–alkaline) differ from the typical rock compositions of the fundamentally basaltic association (Christiansen and Lipman, 1972).

The ages of the two units of the capping volcanic sequence can be used to date two significant events of the Cenozoic record. First, assuming the basal and silicic volcanic sequences reflect a former subduction system off the western United States, the youngest determined dates from this volcanic activity should approximate the age of termination of subduction beneath southeastern California. This age will be younger by a small but unknown time lag during which the terminated edge of the descending plate passes beneath the zone of volcanism. On figure 8B, we define this interval by plotting the youngest dates from the silicic volcanic sequence and the older unit of the capping volcanic sequence. These dates cluster in the interval of 22 to 25 m.y. with the youngest date of 21 m.y. being from a plutonic rock near Mt. Barrow. This age span agrees closely with the age of termination of subduction off coastal southern California following the constant motion model of Atwater (1970) and the revised model of Atwater and Molnar (1973).

Second, the age of transition to fundamentally basaltic volcanism, following the model of Christiansen and Lipman (1972), is generally considered to coincide in time with the onset of extensional faulting and may have been controlled by triple-point migration along the San Andreas system. On figure 8C, we have plotted the ages of the younger unit of the capping volcanic sequence. The ages fall within a range of 13 to 19 m.y. The older age of 22 m.y. for volcanic rocks of the Orocopia Mountains may be influenced by the proximity to the Salton Creek fault, a major tectonic feature during mid-Cenozoic time. Due to difficulties in obtaining datable samples, we have not obtained ages for all occurrences of the younger unit of the capping volcanic sequence. Nonetheless the available dates have considerable significance. The ages (fig. 8C) are clearly younger than the previously cited age (26-23 m.y.) of transition to fundamentally basaltic volcanism in southeasternmost California (Christiansen and Lipman, 1972, p. 259). This conflicts markedly with the suggested northwest decrease in age of the transition to basaltic volcanism in the southwestern United States. In contrast the data of figure 8C suggest a southeastward younging in the volcanic transition. This interpretation is limited, however, both by the size of the region and the relatively small number of dated samples.

Crowe (1978) has presented evidence suggesting an Oligocene age of inception of basin-range faulting in southeasternmost California and further that a transition to basaltic volcanism in this area considerably postdates the inception of faulting. On a regional scale as shown by figure 8C, the age of transition to fundamentally basaltic volcanism is notably younger than the probable age of inception of basin-range faulting. This suggests that the two events are distinctly separate and unrelated. The age of the transition in southeastern California does overlap, however, with the probable mid-Miocene age of inception of movement on the San Andreas fault south of the Transverse Ranges (Crowell, 1975; Ehlig, Ehlert, and Crowe, 1975). Thus in accord with the model of Christiansen and Lipman (1972), the transition to fundamentally basaltic volcanism does appear to be related in timing to the development of the San Andreas transform system. However, our data indicate a notably younger age for the volcanic transition than they suggest. Moreover, the transition appears to be slightly younger than the age of termination of subduction and considerably younger than the probable age of inception of basin-range faulting in southeastern California.

Salton Creek fault.—The Salton Creek fault is a major east-west trending fault between the Chocolate and Orocopia Mountains (fig. 5). The fault is exposed in the central part of the northern Chocolate Mountains where it juxtaposes highly sheared metaigneous basement rocks on the south against north-tilted fanglomerate. The inferred trace of the fault is marked to the west by the Salton Creek dome chain; to the east it may lie buried beneath alluvial deposits on the north side of the Tabaseco Tanks dome field. The dome field forms an east-trending projection of the northern Chocolate Mountains, and individual domes within the field are elongate in an east-west direction. This suggests that the Salton Creek fault may have controlled the surface emplacement of the domes. East of the Tabaseco Tanks domes the Salton Creek fault aligns with an inferred east-trending fault located within a linear valley of the Chuckwalla Mountains (fig. 6). This fault may be the eastern continuation of the Salton Creek fault.

The Salton Creek fault was apparently active during mid-Cenozoic time. The fault and its possible eastern extension in the Chuckwalla Mountains mark the northern boundary for the occurrence of volcanic and plutonic rocks of southeastern California (sequences A and B). The Salton Creek domes dated at 27 and 33 m.y. were apparently emplaced along the fault. If these ages are not anomalous, they provide a minimum age for the development of the fault system. Northwest-trending dike swarms and associated plutonic rocks are apparently truncated by the Salton Creek fault. These plutonic rocks, with the exception of minor dikes, are not present in the Orocopia Mountains. There are marked contrasts in basement-rock geology between the northern Chocolate Mountains and the Orocopia Mountains. The Clements Well fault, a major strike-slip fault within the Orocopia Mountains (Crowell, 1962, 1975), is not exposed to the south in the Chocolate Mountains. It either bends and merges to the southeast with the Salton Creek fault or is truncated by the fault. Volcanic clasts derived from the volcanic rocks of the northern Chocolate Mountains are not present in the Diligencia Formation of the Orocopia Mountains, a nonmarine, Oligo-Miocene sedimentary deposit. Paleocurrent studies of these rocks show local south to north transport directions (Crowell, 1958, unpub. data; Spittler and Arthur, 1973; Bohannon, 1975), and the northern Chocolate Mountains were a volcanic high during Diligencia time.

The above evidence strongly suggests that the Salton Creek fault was an active and major tectonic feature of southeastern California during mid-Cenozoic time. Most notably, the fault bounds a major Cenozoic volcanic and plutonic province. This geologic setting is similar to, but clearly unrelated in space and time, to the two contrasting assemblages of Tertiary volcanic and Tertiary sedimentary rocks in the Lake Mead region (Anderson and others, 1972). Stewart, Moore, and Zietz (1977) have described arcuate east-west trending patterns in age belts of Cenozoic igneous rocks in Nevada and Utah that in part coincide with aeromagnetic anomalies and belts of mineral deposits. Ekren and others (1976) have described east-trending structural lineaments in central Nevada.

The Salton Creek fault is overlapped by volcanic rocks (unit Cb) believed to correspond to the fundamentally basaltic association. Olivine andesite of this sequence crops out both north and south of the projected Salton Creek fault in the Chuckwalla Mountains. Basalt and minor andesite are present in the Orocopia Mountains. The distribution of the younger unit of the capping volcanic sequence contrasts markedly with the distribution of the older sequences. This suggests that with the change in volcanic association and possibly with the inception of the San Andreas system, the Salton Creek fault ceased to be a major tectonic boundary. Moreover, the Salton Creek fault may be related to or possibly the offset equivalent of the Big Pine Fault or east-west trending faults in the Soledad Basin.

The Salton Creek fault parallels major left-slip faults that are important structural elements of the eastern Transverse Ranges province. These faults include the Pinto Mountain fault (Dibblee, 1976b), the Blue Cut fault (Hope, 1966), and the Chiriaco fault (Powell, 1975). Relative offset along the Salton Creek fault is unknown; the absence of volcanic clasts in the Diligencia basin can perhaps be explained by postdepositional strike slip on the fault. However large scale strike slip is precluded by the presence of the southeast-trending, Orocopia thrust system of the Orocopia Mountains (Crowell, 1975) within the central Chocolate Mountains (Murray and Crowe, 1976).

Dillon (ms) has described east-west trending, left-slip faults within the southern Chocolate Mountains. The parallism of these faults and the Salton Creek fault to major faults of the Transverse Range is striking. The inferred movement history of the east-west trending faults of southeastern California suggests that they are not part of the young Transverse Range system. They may represent ancestral elements of an older Transverse range structure.

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APPENDIX 1

Longitude and latitude of sample localities for K–Ar dates

Sample number	Lab number	Longitude	Latitude
5-86	KA1190	114°37′	32°58′
LC-15	KA1263	115°05′	33°28′
AP-2	KA1401	115°16′	33°31′
F-9	KA1587	114°48′	33°18′
SW-1	KA1260	115°42′	33°31′
SW1-3B	KA1290	115°42′	33°31′
CG-57	KA1268	115°25′	33°28′
CG-642	KA1264	115°24′	33°28′
CG-55	KA1267	115°24′	33°29′
F-5	KA1590	115°05′	33°27′
F-2	KA1589	114°52′	33°24′
F-7	KA1583	114°52′	33°22′
F-1	KA1588	114°53′	33°23′
F-10	KA1584	114°48′	33°18′
BH-3	KA1410	115°02′	33°24′
PV-21	KA1287	114°52′	33°23′
F-8	KA1586	114°52′	33°22′
LC-4	KA1402	115°05′	33°27′
CG-32	KA1266	115°33′	33°30′
CG-27	KA1265	115°34′	33°31′
PP-100	KA1407	114°52′	33°05′
PV-34	KA1289	114°52′	33°26′
PV-33	KA1406	114°52′	33°26′
F-3	KA1585	114°52′	33°26′
AP-10	KA1403	115°16′	33°29′
CMG1-36	—	115°21′	33°19′
CMG1-34	—	115°20′	33°20′
CMG1-35	—	115°20′	33°19′
CMG1-68	—	115°34′	33°29′
CG-B	KA1262	115°40′	33°30′

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RELATIONSHIPS AMONG GIBBS ENERGIES OF FORMATION OF COMPOUNDS

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ABSTRACT. Two parameters called ΔO^{2-} cation and mean ΔO^{2-} compound are calculated from the data of Gibbs free energies of formation from the elements of oxides and corresponding aqueous cations. The Gibbs free energies of formation of compounds from their constituent free oxides are shown to vary linearly with ΔO^{2-} cation. The Gibbs energy of formation of a compound from its two constituent oxides calculated per one oxygen in the formula is shown to be a parabolic function of mean ΔO^{2-} compound; the Gibbs energy of reaction for the formation of a compound C intermediate in composition to two compounds A and B, $A + B \longrightarrow C$ is approximated by

$$\Delta G^{\circ}\ \text{reaction} = \alpha\,(\Delta O^{2-}{}_{M1} - \Delta O^{2-}{}_{M2})\, n_0{}^{C}\,(X_1{}^{C} - X_1{}^{A})\,(X_1{}^{C} - X_1{}^{B})$$

INTRODUCTION

Several methods based on corresponding state relationships have been proposed for estimating enthalpies and Gibbs free energies of formation of minerals (compare Karapet'Yants, 1961; Karpov and Kashik, 1968; Eugster and Chou, 1973; Nriagu, 1975). Tardy and Garrels (1976a, b), Tardy and Vieillard (1977), and Tardy and Gartner (1977) developed a method based on an empirical parameter called $\Delta O^{2-}{}_{\text{cation}}$ and defined as:

$$\Delta O^{2-}{}_{M} = \frac{1}{x}\,(\Delta G^{\circ}{}_{f}\ MO_{x(c)} - \Delta G^{\circ}{}_{f}\ M^{2x+}\ (aq))$$

in which M is a given cation, x = cation valence/2, $\Delta G^{\circ}{}_{f}\ MO_{x(c)}$ and $\Delta G^{\circ}{}_{f}\ M^{2x+}$ (aq) are respectively the Gibbs free energies of formation from the elements of the corresponding oxide MO_x and the corresponding aqueous cation M^{2x+}.

For hydroxides, silicates, phosphates, nitrates, and carbonates involving two cations, it was found that the Gibbs free energy of formation of a given compound from its constituent oxides has the general expression:

$$\Delta\ \text{compound} = -\,\alpha\,\frac{n_1 \times n_2}{n_1 + n_2}\,(\Delta O^{2-}{}_{M} - \Delta O^{2-}{}_{M\ \text{ref}}) \qquad (1)$$

in which:

Δ compound = $\Delta G^{\circ}{}_{f}$ compound − $\Sigma\Delta G^{\circ}{}_{f}$ oxides = $\Delta G^{\circ}{}_{R}$ (simple oxides)

$\Delta O^{2-}{}_{M}$ is the parameter ΔO^{2-} for a given cation M

$\Delta O^{2-}{}_{M\ \text{ref}}$ is the parameter ΔO^{2-} for the reference cation, in common in all compounds of the same family (H in hydroxides, Si in silicates, P in phosphates et cetera); α is a coefficient variable from one family of compounds to another one (0.84 for hydroxides, 1.01 for silicates, 1.15 for carbonates, 1.30 for nitrates et cetera); n_1 is the number of oxygens required to balance the cation M in the compound formula; n_2 is the number of oxygens required to balance the reference cation M ref in the compound formula.