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GEOLOGICAL SURVEY

Tectonic Framework of the Mojave and Sonoran Deserts, California and Arizona

Abstracts from a conference held by
the U.S. Geological Survey in
Menlo Park, California, November 4-6, 1980

Edited by
Keith A. Howard, Michael D. Carr, and David M. Miller

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This volume is dedicated to

Charles A. Anderson

in appreciation for pioneering
geologic studies in Arizona
and

Thomas W. Dibblee Jr.

in appreciation for pioneering
geologic studies in southern California

The conference organizers
Michael D. Carr
Gordon B. Haxel
Keith A. Howard
Barbara E. John
Jonathan C. Matti
David M. Miller

FORWARD

A growing number of earth-science investigations are being conducted in southeastern California and southern Arizona. This work is motivated in part by national mandates for hazards and resource appraisals, and in part by the growing recognition of the scientific importance of this region for understanding the evolution of the North American Cordillera. About 300 scientists attended a conference November 4-6, 1980, in Menlo Park, California, to share information toward building a better understanding of the tectonic framework of the Mojave and Sonoran Deserts.

Conference symposia were focused on the following topics:

- Regional framework
- Crustal structure and Precambrian geology
- Late Precambrian and Paleozoic stratigraphy and tectonics
- Mesozoic stratigraphy and thrusting
- Mylonites and metamorphism
- Cenozoic volcanism
- Economic resources
- Detachment faulting
- Cenozoic basin and range boundaries
- Neotectonics
- Geophysics and geophysical transects
- Public policy and future of the desert lands

Eighty-five scheduled speakers and panelists were joined by a lively audience in a stimulating discussion in each session. A conference summary has been published in the April, 1981, issue of the magazine GEOTIMES (vol. 26, no. 4, p. 16-18).

The enthusiasm of the participants and the exciting new results prompted the convenors to call for extended abstracts. The result is this volume, which captures some of the essence of new work presented at the conference.

CONTENTS

CONDITIONS OF MYLONITIZATION IN A CORDILLERAN METAMORPHIC COMPLEX, WHIPPLE MOUNTAINS, CALIFORNIA

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The autochthon of the Whipple Mountains, S.E. California is composed of strongly lineated mylonitic gneisses with a structural thickness in excess of 3.9 km. The development of this penetrative low-angle fabric (Fig. 1) was accompanied and, in part controlled by, synkinematic intrusion of peraluminous and metaluminous granitoid sills (Anderson and Rowley, 1981; Davis et al., 1980) of late Cretaceous age. The extent of mineral reequi-

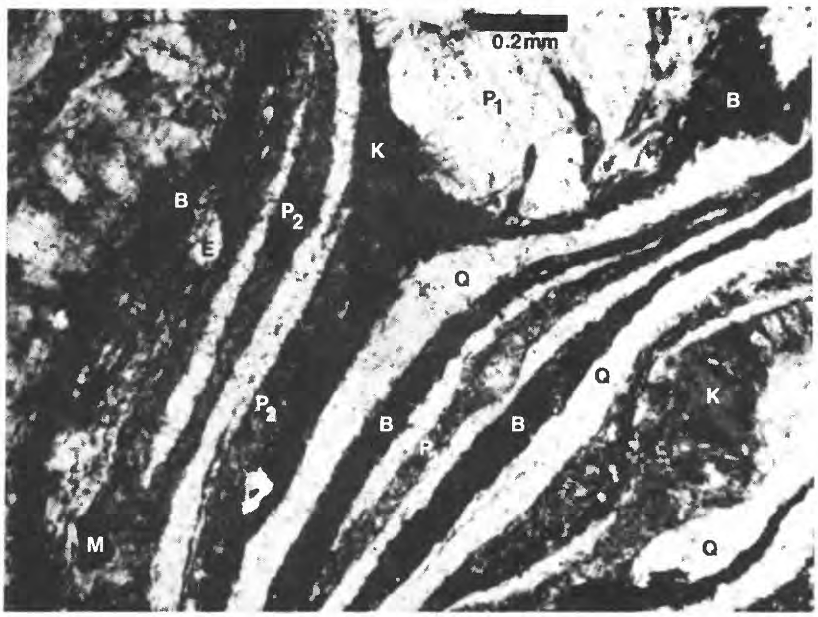

Figure 1. Photomicrograph of a mylonitized granodiorite exhibiting pronounced mineral segregation. Mineral symbols: P_1 and P_2 = porphyroclastic and matrix plagioclase, K = K-feldspar, B = biotite, Q = quartz, M = magnetite, E = epidote.

libration during mylonitization is limited to the ultra-fine grained mylonitic matrix and tension gashes. Garnet exhibits no reequilibration effects while K-feldspar and magnetite are thoroughly reequilibrated. A wide range of composition, commonly bimodal, exist for plagioclase, hornblende, biotite, and muscovite reflecting incomplete reequilibration during mylonitization. Anderson and Rowley (1981) utilized relict primary compositions to estimate conditions of crystallization. For the two-mica, garnet-bearing granitoids this was estimated to be 660-740°C at an elevated oxygen fugacity and depth of 9-10 km. Depth constraints were based on the Mn-rich (19.8-37.4% SP) composition of plutonic garnet and the celadonitic character (Fig. 2) of the plutonic muscovite. As in other two-mica granites the muscovite is rich (19.5-32.5%) in a titaniferous ferri-celadonite "end member" which has an ideal formula of $K(Mg_{0.8}Ti_{0.2})Fe^{3+}Si_{3.6}Al_{0.4}O_{10}(OH)_2$. It is proposed on petrologic grounds that this remarkably common, yet

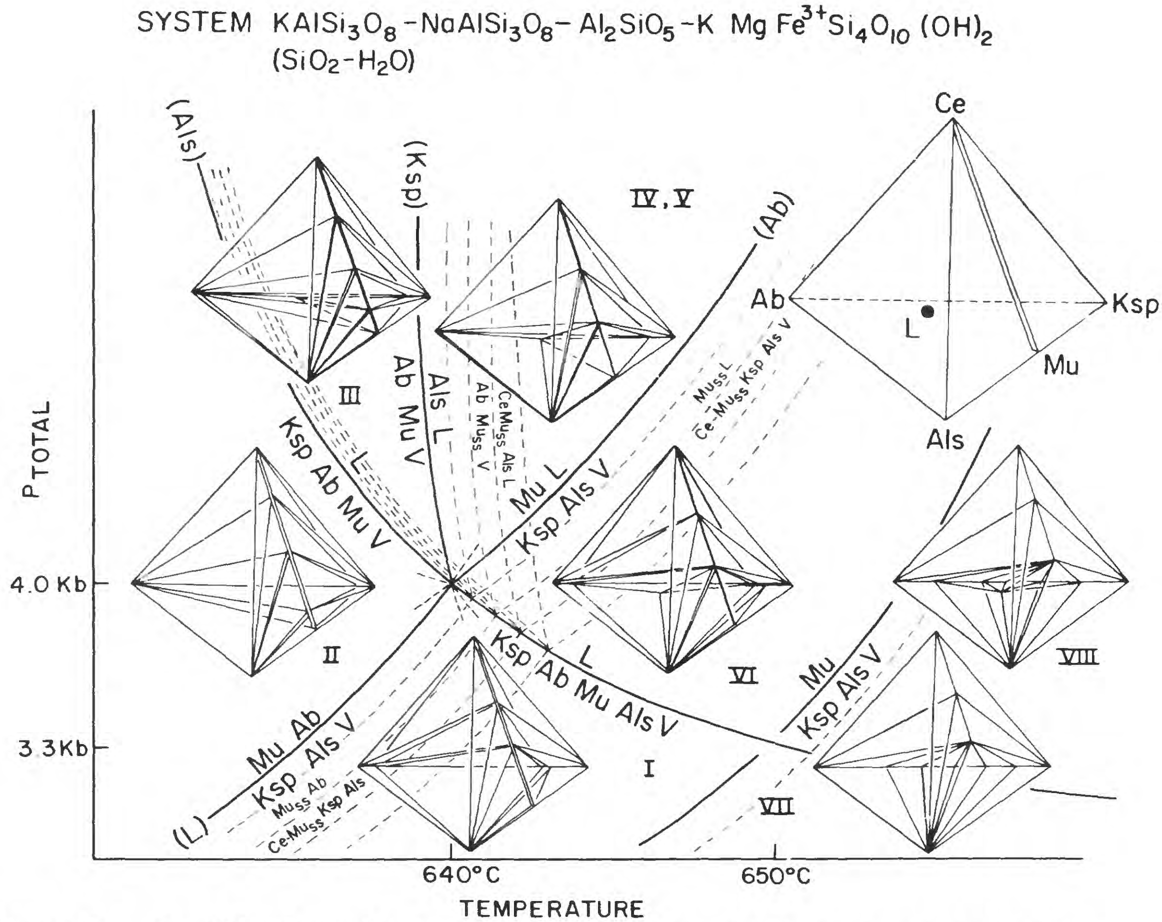

Figure 2. Graphical analysis for phase relations in muscovite-bearing granitic melts. All reactions except Ksp+Ab+Mu+Al_s+V = L are degenerate for the celadonite-free system and represent the initiation of continuous reactions involving increasingly celadonitic muscovite. Muscovite on the above solidus reaction is pure at the degenerate invariancy and becomes increasingly celadonitic with lower pressure.

experimentally not studied, celadonite species extends the stability field of plutonic muscovite and dramatically lowers the pressure at which this phase can equilibrate with near H_2O-saturated silicate melt.

With retrogression during mylonitization, the most apparent affect on this muscovite is depletion in Ti (from 1.0-1.3 wt.% TiO_2 to 0.1-0.3%) with a slight decrease ($\sim$5-6%) in "ferri-celadonite" content. In order of importance, solution mechanisms describing the retrogression include (1) Ti + R^{2+} = $2Al^{VI}$, (2) Si + R^{2+} = Al^{IV} + Al^{VI}, and (3) Fe^{3+} = Al^{VI}. The "celadonite end-member" (18.4-21.6%) of the secondary muscovite approximates $K\,Fe^{3+}Mg\,Si_4O_{10}(OH)_2$. Mylonitized biotite and hornblende both exhibit a depletion in Ti and enrichment in Mg. For biotite, TiO_2 decreases from 2.4-3.8 to 0.6-1.4 wt.% with a principal solution mechanism of Ti + Al^{VI} = 2Mg. Hornblende (from the deepest synkinematic intrusive) is changed with mylonitization to actinolitic hornblende via the following solution mechanisms: (1) $(Na + K)^A + Al^{IV} = \square^A + Si$, (2) $Al^{IV} + Al^{VI} = Si + Mg$, (3) $Fe^{2+} = Mg$, and (4) $Ti + 2Al^{IV} = Mg + 2Si$. Plagioclase porphyroclasts have oscillatory zoning indicating a preservation of primary composition. In the mylonitic matrix, reequilibrated plagioclase is systematically more sodic and ranges An_{03-19} in upper levels and An_{21-24} in deeper levels. Epidote, the only true porphyroblast in the mylonitic rocks, is ubiquitous and attests to this retrogression.

These recorded changes to reequilibrated compositions suggest that the above phases are stable within the P-T regime of mylonitization and thus provide a basis for estimation of the intensive parameters. Because the intrusives are synkinematic, then the above 2.6 kb (9.6 km) estimate applies also to mylonitization. This pressure is also consistent with calculations based on reequilibrated biotite-alkali feldspar-magnetite compositions which indicate maximum pressures of 1.6-3.1 kb (5.9-11.5 km). Feldspar thermometry (Whitney and Stormer, 1979) are an indication of mylonitization temperature (Fig. 3). Despite the range, it seems clear that metamorphic grade (upper greenschist to lower amphibolite) increases with depth. Although there is some model uncertainty in the thermometry calculations, the estimates are consistent with Bio+Ab-Olig+Ep assemblages being stable at upper levels and Hb+Bio+Olig+Ep at deeper levels. For the latter, independent estimates of 500 ± 20°C based on amphibole-plagioclase partitioning (Spear, 1980) are also consistent. The differences in temperature estimates for upper and lower levels reflect an average change of 1.2 km of structural depth, thus indicating a geothermal gradient of 72°C/km. This is not unlike the 50°C/km (Hoisch and Miller, 1981) estimated for the Cretaceous metamorphism within the Old Woman Mountains 60 km to the NW.

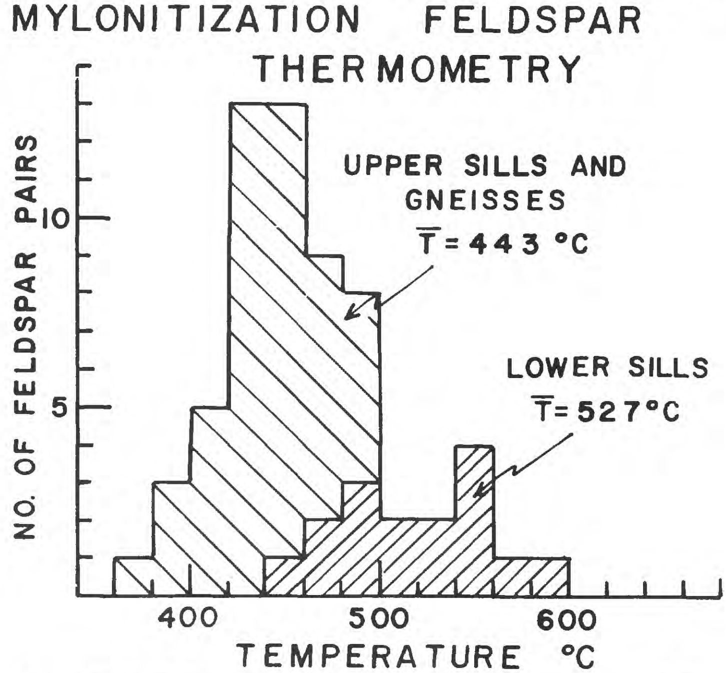

Figure 3. Results of feldspar thermometry for upper and lower levels.

STRUCTURAL TIES BETWEEN THE GREAT BASIN AND SONORAN DESERT SECTIONS OF THE BASIN AND RANGE PROVINCE

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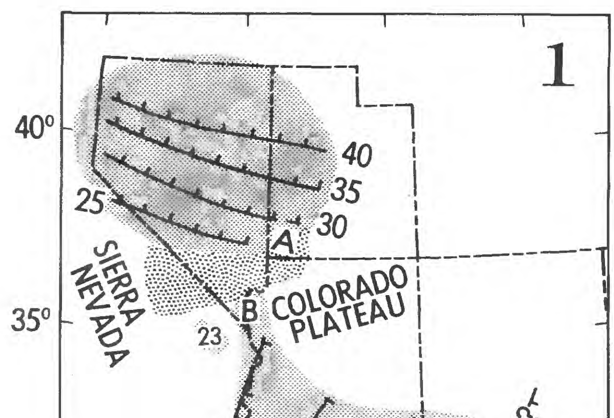
The axis of Cenozoic magmatism migrated south-southwesterly through Nevada and Utah between about 40 and 25 m.y. ago and there is a suggestion of a westerly migration of magmatism from southwest New Mexico across Arizona during the same time interval (fig. 1). Age data and volcanic rock distributions suggest that the magmatism arrived at terminal positions in southwestern Utah and along the Colorado River south of Hoover Dam 21-20 m.y. ago, (A and B in fig. 1) leaving a 100 km-wide amagmatic area between the two terminal positions. The amagmatic area forms the eastern part of a westerly trending corridor that escaped calc-alkalic and bimodal basalt-rhyolite volcanism during Miocene. The relatively amagmatic corridor extends from the Colorado Plateau to the southern Sierra Nevada (fig. 1), embraces a 90 milligal gravity step (Eaton and others, 1978), and is flanked on the north by a zone of diffuse seismicity (Thompson and Burke, 1974). Eaton (1979) referred to the corridor as a boundary zone between the Great Basin (GB) and Sonoran Desert (SD) sections of the Basin and Range province (fig. 1). Because the corridor contains relatively sparse age-datable Miocene igneous rocks, understanding of its Miocene structural history has lagged. Recent geologic mapping, dating of volcanigenic sediments, and evaluations of stress states and kinematic indicators provide a basis for preliminary evaluation of structural ties between the eastern part of the corridor and the adjacent GB and SD sections.



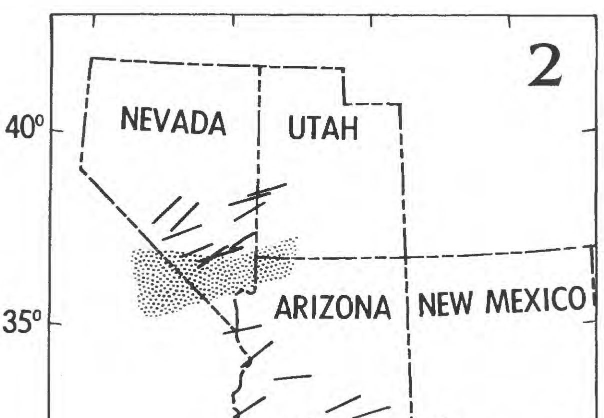


Figure 1.--Map showing patterns of migration of Cenozoic magmatism with calc-alkaline affinities (hachured heavy lines with ages in mega years) modified from Dickinson and Snyder, 1978. The two main areas of magmatism (fine stipple) are separated by an amagmatic corridor that extends from the Colorado Plateau in the Arizona-Nevada border area west to the Sierra Nevada (coarse stipple). A and B mark localities where magmatism began 21-20 m.y. ago.

Figure 2.--Map showing variously derived least principal stress directions within Cenozoic magmatic terrains, from Zoback and others, 1981.

Recent mapping (unpublished) within and north of the eastern part of the corridor in the Beaver Dam and Bull Valley Mountains of southwesternmost Utah and in the Clover Mountains of adjacent Lincoln Co., Nevada reveals a major episode of southerly to southwesterly directed pre Basin-Range thin-skinned extensional tectonic transport. In its early stages this deformation was active as listric growth faults associated with 15-14 m.y. old volcanic activity, but it continued and reached major proportions between about 14 and 11 m.y. ago. During extensional deformation volcanic rocks were structurally transported away from the magmatic axis toward, and, in some places, into the adjacent amagmatic corridor on complex systems of listric and transverse faults. Available data suggest that Precambrian crystalline rocks and Paleozoic and Mesozoic sedimentary rocks within the amagmatic corridor were transported on faults that are similar to, and, in some places, coextensive with those that displace Cenozoic rocks. Locally, Cenozoic volcanic rocks are decoupled from subjacent pre Cenozoic rocks along low-angle fault zones at which there is generally evidence of stratigraphic attenuation. Such decoupling zones are not unique to the base of Cenozoic volcanic rocks, but are also found within the volcanic sequence and in adjacent areas of pre Cenozoic rock. All exposed rocks about 14 m.y. old and older appear to have participated in the episode of south to southwest tectonic transport, the magnitude of which is more dependent on geographic than stratigraphic position.

Similar pre Basin-Range southwest-directed thin-skinned extension of large magnitude occurred in the northernmost SD section south of Hover Dam (Anderson, 1971). The deformation was intense and short-lived--beginning about 15 m.y. ago during the waning stages of the main igneous activity (to which it bears a growth-fault relationship) and ending sometime before about 11 m.y. ago. This extensional tectonism is not only contemporaneous with that in SW Utah and adjacent Lincoln Co., Nevada but also with genetically related large-scale left-slip displacement on the Lake Mead fault system which bounds the extended area on the north (Anderson, 1973, Anderson and Laney, 1975, Bohannon, 1979 and this volume). This important relationship suggests that strike-slip faults responsible for major southwesterly tectonic transport of rocks within the amagmatic corridor interacted with major southwest directed extension in the igneous terrain to the south forming an integrated kinematic system.

Available data, including slip lineations from fault systems within and adjacent to the eastern part of the amagmatic corridor suggest that complex coeval extensional structures entered the corridor from the north, passed through it, and splayed southward across its south margin thus providing structural ties between the GB and SD sections of the Basin and Range province. This suggestion accords well with a recent compilation of variously derived Miocene least principal stress directions (Zoback and others, 1981) which show a remarkable consistency of southwest orientations over a broad region (fig. 2). Ongoing studies of the Cenozoic geology within and adjacent to the eastern part of the amagmatic corridor by R. G. Bohannon, Ivo Lucchitta, and me are partly directed toward evaluating the merrit of the suggestions and interpretations noted herein.

REFERENCES

Anderson, R. E., 1971, Thin-skinned distension in Tertiary rocks of southeastern Nevada: Geological Society of America Bulletin, v. 82, p. 43-58.

_____1973, Large-magnitude late Tertiary strike-slip faulting north of Lake Mead, Nevada: U.S. Geological Survey Professional Paper 794, 18 p.

Anderson, R. E., and Laney, 1975, The influence of late Cenozoic stratigraphy on distribution of impoundment-related seismicity at Lake Mead, Nevada-Arizona: U.S. Geological Survey Journal of Research, v. 3, no. 3, p. 337-343.

Bohannon, R. G., 1979, Strike-slip faults of the Lake Mead region of southern Nevada, in Armentrout, J. M., Cole, M. R., and Terbest, Harry, eds., Cenozoic paleogeography of the Western United States in Pacific Coast Paleogeography Symposium 3: Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 129-139.

Dickinson, W. R., and Snyder, W. S., 1978, Plate tectonics of the Laramide orogeny: Geological Society of America Memoir 151, p. 355-366.

Eaton, G. P., Wahl, R. R., Prostka, H. J., Mabey, D. R., and Kleinkopf, M. D., 1978, Regional gravity and tectonic patterns: Their relation to late Cenozoic epeirogeny and lateral spreading in the western Cordillera, in Smith, R. B., and Eaton, G. P., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 51-92.

Eaton, G. P., 1979, A plate-tectonic model for late Cenozoic crustal spreading in the western United States, in Riecker, R. E., ed., Rio Grade rift: Tectonics and magmatism: American Geophysical Union, Washington, D.C., p. 7-32.

Thompson, G. A., and Burke, D. B., 1974, Regional geophysics of the Basin and Range province: Earth and Planetary Science Annual Review, v. 2, p. 213-238.

Zoback, M. L., Anderson, R. E., and Thompson, G. A., 1981, Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States, Philosophical Transactions, Royal Society of London, in press.

Middle and late Tertiary tectonics of a part of the Basin and Range Province in the vicinity of Lake Mead, Nevada and Arizona

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Dominant Tertiary structural features in the southeastern Great Basin and northeastern Sonoran Desert in the vicinity of Lake Mead are north-trending Basin and Range structures, widespread pre-Basin and Range normal and listric normal faults accompanied by rotational stratal tilting, large areas affected by pre-Basin and Range surficial crustal extension, and two large displacement strike-slip fault zones (fig. 1). These two strike-slip fault zones are the northwest-trending Las Vegas Valley shear zone that has about 40 to 65 km of right-slip (Stewart, 1967) and the northeast-trending Lake Mead fault system that has about 65 km of left-slip (Anderson, 1973; Bohannon, 1979, and unpub. data). The Las Vegas Valley shear zone intersects at a high angle with the Lake Mead fault system. The Lake Mead system extends from the Virgin River Valley to a southwestern termination in Eldorado Valley (Bohannon, 1979). Anderson (1971) described a widespread region east of this termination that

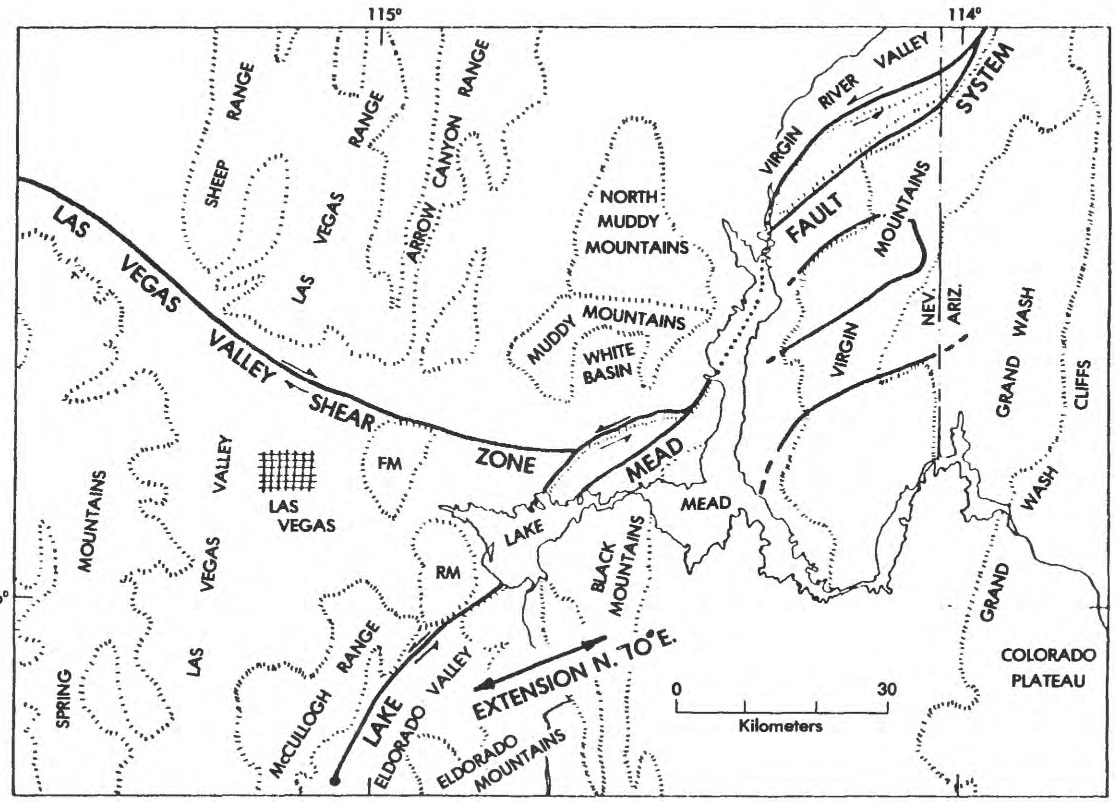

Figure 1.--Index map of the Lake Mead region, Nevada and Arizona, showing several of the major tectonic elements discussed in the text. FM, Frenchman Mountain; RM, River Mountains.

was affected by mid-Tertiary surficial crustal extension that took place within abundant, distinct, fault-bounded structural units that are highly distended by closely spaced north- to northwest-trending listric normal faults. Although the magnitude of this extension is not known, its least principal stress direction is consistently oriented N. 70° E. (fig. 1).

Palinspastic restoration of displacement and distortion caused by movement on the aforementioned structural features is necessary prior to reconstruction of the middle and late Tertiary tectonic history of the area. With palinspastic restoration, a large, structurally simple, north-trending, basement-cored, Sevier- or Laramide-age arch can be defined that dominated the pre-20 m.y. geology of the Lake Mead region east of the Sevier thrust belt. On unrestored geologic maps, components of the arch are disguised by Tertiary rocks and are disrupted by Tertiary deformation, but are nonetheless recognizable. The core of the arch is between the Eldorado-Black Mountains and the Colorado Plateau in the same area that was affected by later crustal extension (Anderson, 1971). Here volcanic rocks, approximately 20 m.y. old, rest directly on Precambrian crystalline rocks, indicating the presence of a widespread, nearly featureless, pre-volcanic and pre-extensional erosion surface (Anderson, 1971; Anderson and others, 1972). Part of the east flank of the arch is preserved on the Colorado Plateau, where Paleozoic and Mesozoic strata dip gently northeast away from the pre-20 m.y. erosional area, a relation in existence prior to a least 18 m.y. ago (Young, 1970; Lucchitta, 1979). The nose and western flank of the arch can be defined between Frenchman Mountain and the Spring Mountains having been offset from the east flank and core by the Lake Mead fault system.

A thin, but widespread veneer of alluvial, fluvial, and lacustrine sediment (Rainbow Gardens Member, Horse Spring Formation) was deposited sometime between 20 and 16.5 m.y. ago in the region of the nose and northeastern flank of the arch. At about the same time, ash-flow tuffs spread over the core and eastern flank. Although conditions at basin boundaries and relations between sediment and volcanic rocks are uncertain, there probably was little deformation associated with basin development.

The nose and northeastern flank of the arch were highly deformed between 16.5 and 14 or 13.5 m.y. ago, when a deep fault-bounded basin formed and was filled with coarse clastic alluvial and clastic lacustrine sediment (Thumb Member, Horse Spring Formation). East-west- to northeast-trending faults, some that possibly have lateral motion components, probably formed the northern and southern margins of this basin, but most aspects of other margins are poorly understood. Andesitic stratovolcanos were built and ash-flow tuffs were erupted south of this basin in the region that previously was the core of the arch. Major strike-slip faulting on the Las Vegas Valley shear zone and Lake Mead fault system and their associated crustal extenstion probably started about 14-15 m.y. ago, but actual documentation of their initiation time is lacking.

By 13.5 m.y. ago, both major fault systems were active and the crust was extending south of Lake Mead. Activity on this intracontinental transform-transform-extension system continued until at least 12 or 11.5 m.y. ago. During this time period, lacustrine deposits with coarse-grained alluvial fault-margin facies formed (Bitter Ridge Limestone and Lovell Wash Members, Horse Spring Formation) northwest of the Lake Mead fault system. South of that system, andesitic to rhyolitic lavas accumulated in eastward-thickening, fault-controlled wedges within the actively extending terrain (Anderson, 1971; Anderson and others, 1972).

During the waning stages of strike-slip activity about 11.5 to 10 m.y. ago, White Basin and the Grand Wash trough formed during an early episode of Basin and Range deformation. Widespread Basin and Range deformation overprinted all older structures sometime between 10 and 5 m.y. ago, but by this time White Basin had apparently ceased subsiding. The clastic deposits that fill the Basin and Range valleys (Muddy Creek Formation) overlap most older structures.

References

Anderson, R. E., 1971, Thin-skinned distension in Tertiary rocks of southeastern Nevada: Geological Society of America Bulletin, v. 82, p. 43-58.

______1973, Large-magnitude late Tertiary strike-slip faulting north of Lake Mead, Nevada: U.S. Geological Survey Professional Paper 794, 18 p.

Anderson, R. E., Longwell, C. R., Armstrong, R. L., and Marvin, R. F., 1972, Significance of K-Ar ages of Tertiary rocks from the Lake Mead region, Nevada-Arizona: Geological Society of America Bulletin, v. 83, p. 273-288.

Bohannon, R. G., 1979, Strike-slip faults of the Lake Mead region of southern Nevada, *in* Armentrout, J. M., Cole, M. R., and Terbest, Harry, eds., Cenozoic paleogeography of the Western United States *in* Pacific Coast Paleogeography Symposium 3: Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 129-139.

Lucchitta, Ivo, 1979, Late Cenozoic uplift of the southwestern Colorado Plateau and adjacent lower Colorado River region: Tectonophysics, v. 61, p. 63-95.

Stewart, J. H., 1967, Possible large right-lateral displacement along fault and shear zones in the Death Valley-Las Vegas area, California and Nevada: Geological Society of America Bulletin, v. 78, p. 131-142.

Young, R. A., 1970, Geomorphological implications of pre-Colorado and Colorado tributary drainage in the western Grand Canyon region: Plateau, v. 42, no. 3, p. 107-117.

STRATIGRAPHY AND STRUCTURE OF A PORTION OF THE BRISTOL MOUNTAINS, SAN BERNARDINO COUNTY, CALIFORNIA

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INTRODUCTION

Approximately 3000 feet of complexly deformed metasedimentary strata are present in the southern Bristol Mountains of central San Bernardino County, California (Fig. 1). These strata were previously mapped only in reconnaissance (C.D.M.G., 1964), and they were considered to be "pre-Cretaceous". My detailed study however shows that these metasediments can be divided into formations and members and correlated with Paleozoic Cordilleran cratonic platform facies rocks in adjacent areas. The complex structure of the strata is the result of repeated folding and faulting events during Mesozoic and Cenozoic time.

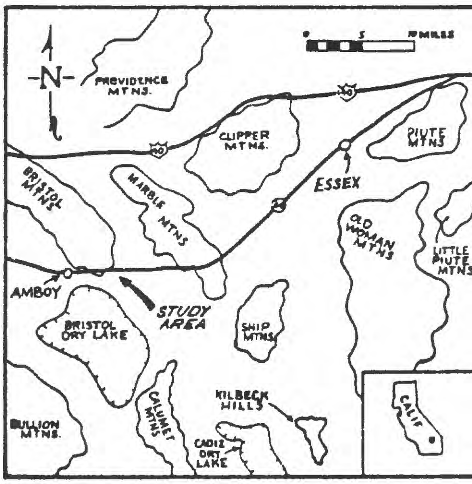

Figure 1. Index map showing location of study area.

STRATIGRAPHY

Metasedimentary strata have been assigned to the following formations listed from oldest to youngest: Cambrian Tapeats Sandstone, Cadiz Member of the Carrara Formation, Bonanza King Formation including lower Muav Limestone Member and upper Banded Mountain Member. Devonian Sultan Limestone (three informal members), Mississippian Monte Cristo Limestone including Dawn, Anchor, and Bullion Members, and Pennsylvanian Bird Spring Formation. Figure 2 is a generalized stratigraphic column with a brief description of each formation. Deformation of most units precludes measurement of true thickness, and the thicknesses shown are tectonic.

Examination of roof pendants in several areas of the Mojave region allows correlation of stratigraphic units. Correlations are based on lithologic similarities (with respect to general lithology and specific distinctive characteristics of the rocks) and stratigraphic sequences. Recognizable, though non age diagnostic fossils were observed in strata assigned to the Bonanza King and Bird Spring Formations.

The Cambrian section in the Bristol Mountains is nearly identical with the upright, relatively undeformed Cambrian sections in the Ship and Marble Mountains. The units in the Bristol Mountains however are structurally attenuated, and the Latham Shale and Chambless Limestone Members of the Carrara Formation have been cut out by faulting. The distinctive pair, Cadiz Member of the Carrara Formation and Muav Limestone allowed facing direction to be determined in many places. The section in the Bristol Mountains is often overturned, and many folds are inverted.

Strata lying between Bonanza King Formation and Sultan Limestone are not present. Lack of Ordovician and Silurian strata is to be expected in Paleozoic sections of cratonic platform affinities.

Strata of late Paleozoic age are predominantly recrystalized to marble, but they retain many identifying characteristics and closely resemble Sultan Limestone and Monte Cristo Limestone from several areas of the region. Correlation of the strata with the Bird Spring Formation is tentative because the basal sandy member widely exposed elsewhere, is missing. The rocks however, are fossiliferous, and lithologically resemble Bird Spring Formation from other areas.

Quartzite, conglomerate, and metavolcanic rocks are exposed adjacent to the study area and may be equivalent to the Early Jurassic Aztec Sandstone and Delfonte Volcanics or Mesozoic metavolcanic and sedimentary rocks described from the New York Mountains (Burchfiel and Davis, 1977).

PALEOZOIC STRATIGRAPHY BRISTOL MOUNTAINS

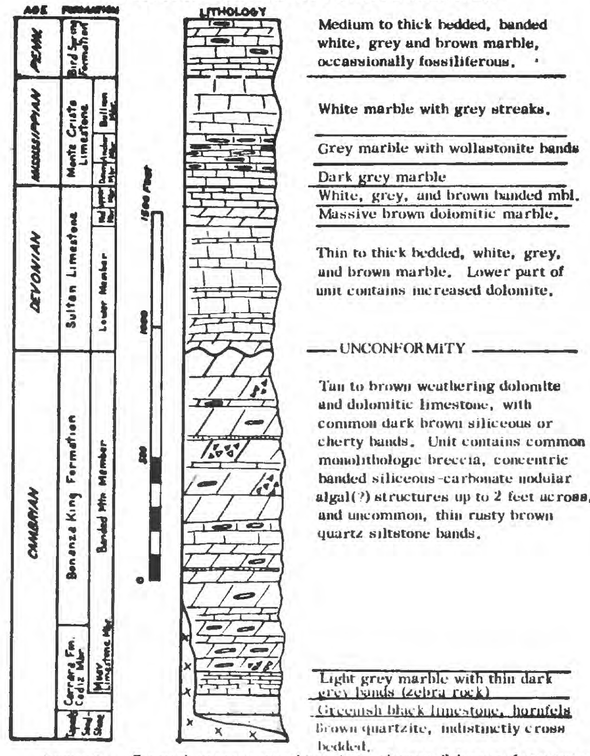

Figure 2. Generalized stratigraphic column showing Paleozoic formations exposed in the Bristol Mountains.

INTRUSIVE ROCKS

Two episodes of intrusion occurred in the Bristol Mountains. Following Early to Middle Mesozoic deformation, the metasediments were intruded and contact metamorphosed (M_1) by sills, stocks, and dikes of syenite, which has yielded K-Ar ages of 139-151 m.y. (Late Jurassic) (Dave Miller U.S.G.S. pers. comm.).

The younger intrusive event emplaced dark colored lamprophyre dikes, which contain orthoclase, olivine, and arfvedsonite, suggesting crystalization from an alkalic magma. Intrusion caused recrystallization (M_2) of adjacent cherty carbonate rocks to wollastonite. These dikes post date all folding but are cut by high angle faults and low angle gravity slides of possible Miocene age. Age relationships therefore indicate a pre Miocene Cenozoic or Late Mesozoic age.

STRUCTURE

Complex structures in the Bristol Mountains are the result of numerous and prolonged deformational events ranging from Early and or Middle Mesozoic to Late Cenozoic time.

During Early or Middle Mesozoic time, an important deformational event occurred, resulting in development of a complex pattern of thrust faults and folds. Reconstruction of the chronologic sequence of events (Fig. 3) envisions overturning of the lower part of the stratigraphic section (Tapeats, Carrara and Muav Limestone Member of the Bonanza King Formation), as it was overidden by a west-directed upright thrust plate (TF_1). Accompanying this thrusting was development of F_1 isoclinal, overturned to recumbent, nw-vergent folds, forming among others, the major fold structure in the range, a large N. 20°E. plunging overturned syncline. Closely following during the continuing event was formation of F_2 folds, which are N. 60°E.-S. 60°W. trending overturned to recumbent, tight to isoclinal se-vergent inverted folds. Following was intrusion of syenite and the development of east directed thrusting (TF_2).

Early folding (F_1, F_2) and thrust faulting events (TF_1) affected and hence postdatesprobable Aztec Sandstone and Delfonte Volcanic strata that are exposed in adjacent areas, and predate intrusion of the syenite (139-151 m.y. K-Ar). F_1, F_2 and TF_1 thus occurred in Early and or Middle Jurassic time. TF_2 probably closely followed or accompanied intrusion of the syenite.

Younger folds include: Major (F_3) shallow plunging N. 60°- 80°W. trending, open to tight, upright to overturned folds. Folds of F_3 generation post date the syenite, and predate younger thrust faulting (TF_3), and are provisionally assigned a Late Mesozoic age. Youngest folds (F_4), are moderate to steeply plunging, north-south trending, open to moderate warps and folds, of probable Cenozoic (Tertiary?) age.

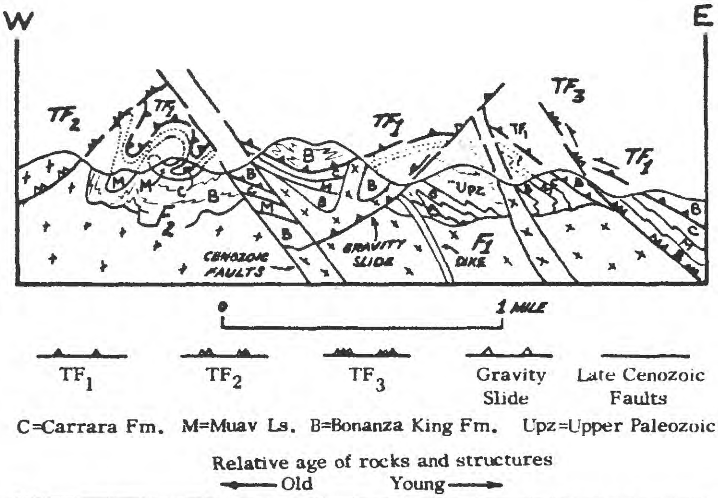

Figure 3. Simplified diagramatic cross section thru the Bristol Mountains showing complex thrust and fold relationships developed during Mesozoic deformation. Note, vertical scale is greatly exaggerated and topography is only approximate.

The Paleozoic rocks have been subjected to many younger episodes of faulting and several major trends are present. Several moderate (35° - 60°) east dipping reverse separation faults (TF_3) are present, and the stratigraphic throw on one fault exceeds 2000 feet. TF_3 post dates F_3 folding, but predates intrusion of the lamprophyre dikes and is tentatively assigned a Late Mesozoic-Early Cenozoic (Larimide?) age.

A fairly recent and conspicuous feature are west dipping low angle gravity slide (?) normal faults. Hanging wall blocks over 500 feet thick appear to have moved toward the southwest, and rotation of the blocks about a vertical axis has also occurred. Some blocks can be shown to have moved at least 500 feet. A Miocene age is inferred for these structures.

Many moderate to steeply dipping normal and reverse faults are present and major trends are north, northwest, east-west, and northeast. Cross cutting relationships suggest that these faults represent several episodes of deformation ranging from Mesozoic through Late Cenozoic age.

ACKNOWLEDGEMENTS

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REFERENCES CITED

Burchfiel, B.C., and Davis, G.A., 1977, Geology of the Sagamore Canyon Slaughterhouse Spring area, New York Mountains California. Geol. Soc. America Bull., v. 88, p. 1623-1640.

Geologic Map of California, Needles Sheet 1964. Calif. Division of Mines and Geology. Scale 1:250,000.

URANIUM IN THE EASTERN MOJAVE AND WESTERN SONORAN DESERTS, CALIFORNIA, NEVADA AND ARIZONA

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The characteristics of 245 reported uranium deposits in the eastern Mojave and western Sonoran Deserts of southeastern California, southern Nevada and western Arizona are catagorized by host rock and grade as an aid to exploration. Hypothetical uranium resources to inferred marginal reserves, based on the current (January 1981) exchange value, are most likely to be discovered in pegmatites, Paleozoic clastic deposits, Tertiary volcaniclastic and lacustrine deposits, and along intrusive contacts.

Uranium occurrences in the eastern Mojave and western Sonoran Deserts may be divided into 18 host environments by rock type and groundwater salinity (fig. 1). A uranium occurrence is defined as a reported deposit with greater than 0.01% U_3O_8 in rock or 20 ppb U in groundwater. A reported deposit is assumed to exceed 100 tons of uranium.

Uranium deposits in igneous environments are reported in intrusive rocks and pegmatites of Precambrian and Mesozoic age, volcaniclastic deposits and volcanic flows of Tertiary age, and along intrusive contacts. Secondary uranium minerals, expecially autunite and carnotite, are either concentrated in veins or disseminated in Precambrian granite and in Mesozoic granite, quartz monzonite and granodiorite. Larsen and Gottfried (1961) report an average grade of 0.00018 to 0.0002% U_3O_8 for Mesozoic granodiorite to quartz monzonite, respectively, within the Mojave Desert. Higher grade deposits are reported in pegmatites in the Cerbat Mountains, Arizona (fig. 2.1) and the New York Mountains, Nevada (fig. 2.2). Hewett (1950) reports cyrtolite and betafite in a layered pegmatite in the Cady Mountains, California (fig. 2.3). Carnotite and other secondary uranium minerals are reported along joints and fractures in Tertiary silicic tuffs in southern Nevada and in Cenozoic rhyolite flows in Death Valley (fig. 2.4). Otton and others (1979) report a calicum uranyl phosphate mineral in hydrothermally-altered Tertiary rhyolite southeast of Essex, California (fig. 2.5). Finally, uranium may be concentrated along contacts between silicic rocks and gneiss, schist or carbonate rocks. Low concentrations of uranium are associated with thorium minerals along sheared contacts between Precambrian shonkinite and gneiss or schist in the Mountain Pass District (fig. 2.6). Otton and others (1980) report uranophane along a sheared contact between Jurassic alkalic quartz syenite and Paleozoic carbonate rocks in the Bristol Mountains, California (fig. 2.7).

Uranium deposits in sedimentary environments are reported in carbonate rocks of Paleozoic age and in clastic deposits of Paleozoic to Quaternary age. Clastic deposits include Paleozoic to Tertiary sandstone, quartzite and conglomerate as well as Tertiary lacustrine and Quaternary alluvial deposits. Uranium minerals are associated with limonite and copper oxides in veins and siliceous lenses in limestone and dolomite in and adjacent to the Spring Mountains, Nevada (fig. 2.8). The Green Monster Mine (fig. 2.9) produced 5 tons of 1.09% U_3O_8 from carbonate rocks in the Spring Mountains in 1951 (Garside, 1973). Carnotite is found as a coating on bedding planes, joints, faults, fractures, and on pebbles in Paleozoic sandstone, quartzite and conglomerate deposits as well as in Tertiary sandstone overlying Paleozoic carbonate rocks in the Spring Mountains. Uranophane and autunite are reported in Mesozoic quartzite and conglomerate deposits in the McCoy Mountains, California (fig. 2.10). Secondary uranium minerals, generally carnotite, are reported in Tertiary tuffaceous lacustrine deposits in the Date Creek Basin (fig. 2.11) and east of Detrital Wash, Arizona (fig. 2.12) as well as in the Lake Manix area, California (fig. 2.13). The Anderson Mine (fig. 2.14) produced 26.6 tons of 0.15% U_3O_8 from lacustrine deposits in the Date Creek Basin from 1955 to 1959 (Sherborne and others, 1979). Carnotite or tyuyamunite is found as a coating on pebbles in Quaternary alluvial deposits and caliche-cemented gravels east of the Spring Mountains.

Uranium deposits in metamorphic environments are reported in gneiss, schist, and metasedimentary rocks. Uranium associated with thorium minerals is reported in small roof pendants of biotite gneiss at the northeastern end of the San Bernardino Mountains (fig. 2.15), in biotite-rich zones of the Precambrian Pinto Gneiss in the Pinto Mountains (fig. 2.16), disseminated in gneiss intruded by granite, pegmatite and aplite dikes in the Pinto (fig. 2.17) and Little San Bernardino Mountains (fig. 2.18), and within fault zones in biotite schist west of Twentynine Palms, California (fig. 2.19). Pitchblende(?) is reported in fault zones within Precambrian gneiss in the Cerbat Mountains (fig. 2.20) and in fissures in the Precambrian Yavapai Schist near Bagdad, Arizona (fig. 2.21). Uraninite veins in fault zones are reported in undivided gneiss and schist in the Cerbat (fig. 2.22) and Hualapai Mountains, Arizona (fig. 2.23). Carnotite and other secondary uranium minerals are found as a coating along fractures and in quartz veins in metasedimentary rocks, primarily metalimestone, in the El Dorado Mountains, Nevada (fig. 2.24) and in the Clark (fig. 2.25) and Old Dad Mountains California (fig. 2.26).

Dissolved uranium is most often reported in greater concentrations in fresh groundwater (i.e., specific conductance less than 1500 umhos/cm at 25°C) than in saline groundwater (specific conductance greater than 150 umhos/cm). Uranium concentrations generally range from 30 to 300 ppb in fresh groundwater and from 23 to 110 ppb in saline groundwater. The maximum reported concentration is 650 ppb U at Lucerne Dry Lake, California (fig. 2.27).

Vertical dashed lines along the right side of figure 1 indicate the average cut-off grade at various forward cost determined by DOE. The current (January 1981) uranium exchange value fixes the current cut-off grade at approximately 0.1% U_3O_8. These economic factors suggest that hypothetical uranium resources to inferred marginal reserves in the eastern Mojave and western Sonoran Deserts are most likely to be discovered in sandstone, quartzite, and conglomerate deposits of Paleozoic age, in layered pegmatites of Mesozoic age, in silicic tuffs and tuffaceous lacustrine deposits of Tertiary age, and along sheared intrusive contacts between silicic igneous rocks and gneiss, schist or carbonate rocks.

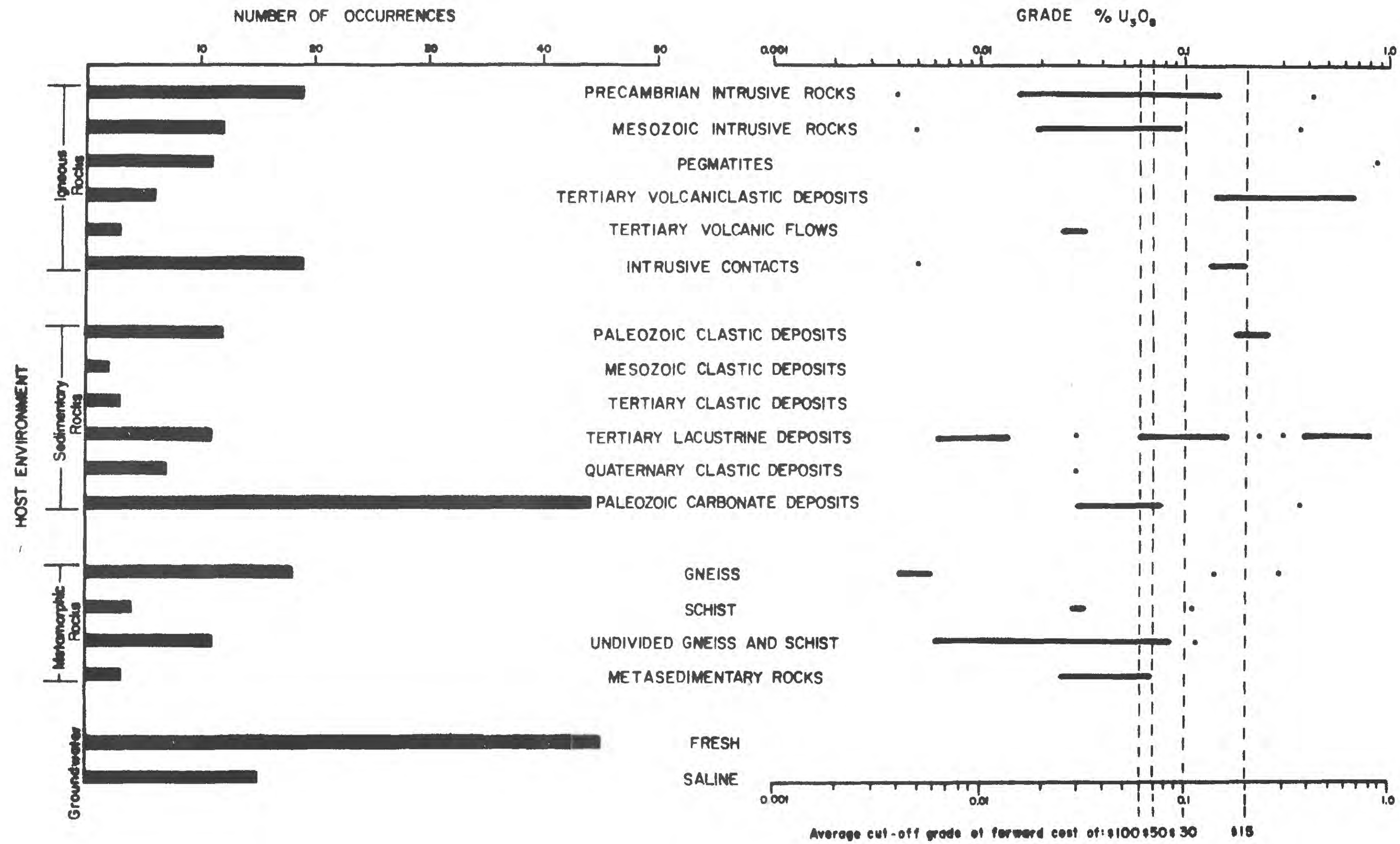

Figure 1. Histogram of number of occurrences and log-normal plot of grade vs. host environment for reported uranium deposits in the eastern Mojave and western Sonoran Deserts, California, Nevada and Arizona.
[Solid lines represent range in grade for given host rock, dots represent reported grade for single deposit]
n = 245

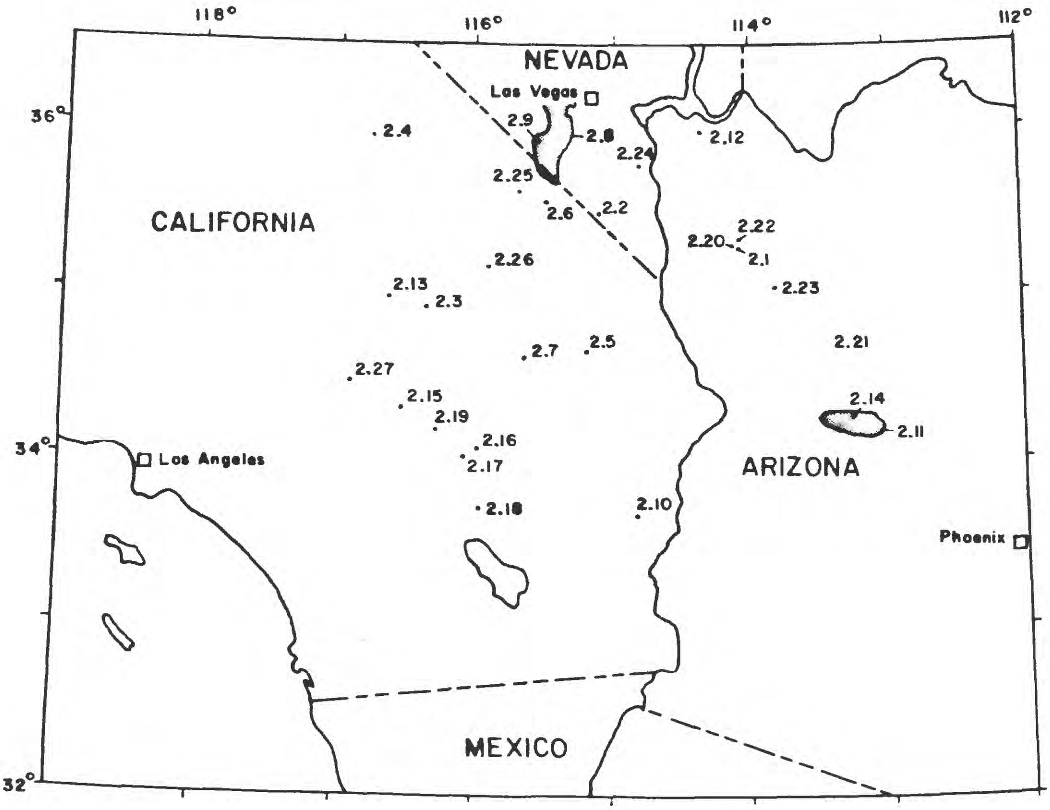

Figure 2. Location map of uranium deposits described in text.

REFERENCES

Garside, L.J., 1973, Radioactive mineral occurrences in Nevada: Nevada Bureau of Mines and Geology Bulletin 81, 121p.

Hewett, D.F., 1950, Uranium occurrence at the Hoerner-Ross Pegmatite, Cady Mountains, San Bernardino County, California: U.S. Geological Survey Trace Elements Memorandum Report 144, 8p.

Larsen, E.S., Jr., and Gottfried, David, 1961, Distribution of uranium in rocks and minerals of Mesozoic Batholiths in western United States: U.S. Geological Survey Bulletin 1070-C, 40p.

Otton, J.K., Glanzman, R.K., and Brenner-Tourtelot, Elizabeth, 1979, A uranium occurrence in an altered volcanic flow near Essex, California: U.S. Geological Survey Open-File report 79-1523, 6p.

---------------- 1980, Uranium, rare-earth, and thorium mineralization at the Hope Mine, eastern Bristol Mountains, San Bernardino County, California: U.S. Geological Survey Open-File Report 80-821, 18p.

Sherborne, J.E., Jr., Buckovic, W.A., DeWitt, D.B., Hellinger, T.S., and Pavlak, S.J., 1979, Major uranium discovery in volcaniclastic sediments, Basin and Range Province, Yavapai County, Arizona: American Association Petroleum Geologist Bulletin, v. 63, 621-646p.

WESTERN FACIES PALEOZOIC ROCKS IN THE MOJAVE DESERT, CALIFORNIA

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INTRODUCTION

Rocks of the El Paso Mountains, just north of the Garlock fault in Kern County, California (fig. 1), provide a stratigraphic and structural key to western-facies Paleozoic rocks in the southern Cordillera. An assemblage of complexly deformed and metamorphosed eugeosynclinal rocks of known and probable Paleozoic age--the Garlock Formation and Mesquite Schist of Dibblee (1952, 1967)--crops out in the central and eastern part of the range. The metamorphic assemblage is intruded by or faulted against uppermost Permian and/or lower Mesozoic plutons (Christiansen, 1961; Cox and Morton, 1980). The Garlock assemblage and correlative rock assemblages in the western Mojave Desert (fig. 1) figure prominantly in tectonic reconstructions of the Cordillera because of their apparently anomalous position with respect to western-facies Paleozoic rocks in Nevada and to recognized lower Paleozoic paleogeographic trends.

GARLOCK ASSEMBLAGE

The Garlock Formation of Dibblee is a stratigraphically and structurally complex assemblage of deepwater marine metasedimentary and metavolcanic rocks, which Dibblee (1967) mapped as twenty-two lithologic units (fig. 2). Our new data are discussed relative to the map units of Dibblee for spatial reference only. The entire Garlock assemblage is complexly deformed in northwest-trending folds that have gently plunging axes and steeply east-dipping axial planes. Map-scale folds are typically faulted in their hinge areas, and few fold closures crop out, giving the assemblage the appearance of a homoclinally east-dipping sequence more than 12,000 m thick. Dibblee (1952) found probably Early Permian fusulinids near the middle of the Garlock (his unit 12) and suggested that his formation might be Permian or younger in its structurally higher part to the east and Permian or older to the west, but recognized that the sequence was probably thickened by folding. Poole and others (1977), Poole and Sandberg (1977) and Poole and Christiansen (1980) found additional fossils indicating that Ordovician and Devonian rocks are present in the western part of the Garlock assemblage (Dibblee's units 5,7 and 9). In addition, Poole (1974) tentatively correlated unfossiliferous flysch-like rocks in the central part of the assemblage (Dibblee's units 10-11) with the Carboniferous Antler synorogenic rocks of Nevada, based on similiar tectonic and stratigraphic positions and lithologies. New mapping and conodont-based age determinations indicate that, in addition to unit 12, Dibblee's units 14 and 15 are Permian. These new data also indicate that much of the Garlock assemblage east of unit 15 is early Paleozoic in age and that Pennsylvanian rocks are also present locally. The contact between the Garlock assemblage and Dibblee's Mesquite Schist to the west is generally a fault. Christiansen (1961) demonstrated that there is no significant metamorphic discontinuity between the Mesquite and Garlock assemblages. Small-scale structures indicate that juxtaposition and deformation of the two lithologic assemblages predate or were synchronous with intrusion of plutons west of the metasedimentary rocks. The Mesquite is lithologically more like lower Paleozoic rocks in the east part of the Garlock assemblage than rocks adjacent to the Mesquite-Garlock contact.

Two contrasting sequences of lower Paleozoic continental-rise or slope-facies rocks are recognized in the Garlock assemblage. In the west part of the assemblage are interbedded chert and fine-grained siliceous clastic and metavolcanic rocks deposited in a continental rise environment. In the east, more calcareous strata are interbedded with the siliceous clastic rocks, which are partly age equivalent to the lower Paleozoic rocks in the west but were deposited in an upper continental-rise or slope environment.

The western units (Dibblee's units 1-9) comprise chert, argillite and siltite, pillowed greenstone, chert-pebble conglomerate, quartzite, and sandy and silty carbonate rocks (Christiansen, 1961; Poole and Christiansen, 1980). Many of the argillite and siltite units are thinly bedded and locally graded, and probably are fine-grained turbidites. The argillites locally contain Nereites-ichnofacies fossils indicating deep-water deposition. Poole and Christiansen (1980) reported Ordovician and Devonian fossils from Dibblee's units 5,7, and 9; no diagnostic fossils are available from the other units in the west part of the assemblage, but they are presumed to be of early and middle Paleozoic age, as well.

Lower Paleozoic rocks are also present in the structurally high eastern parts of the Garlock assemblage (Dibblee's units 18-21). The lower Paleozoic sequence in the east part of the assemblage, complexly repeated by folding and faulting, consists of units with thinly interbedded limestone, siltstone, and chert, as well as other units of, bedded chert, limestone and silty limestone, quartzite, slate, and, locally, greenstone. A distinctive interlayered quartzite and black-slate unit, which is repeated at least four

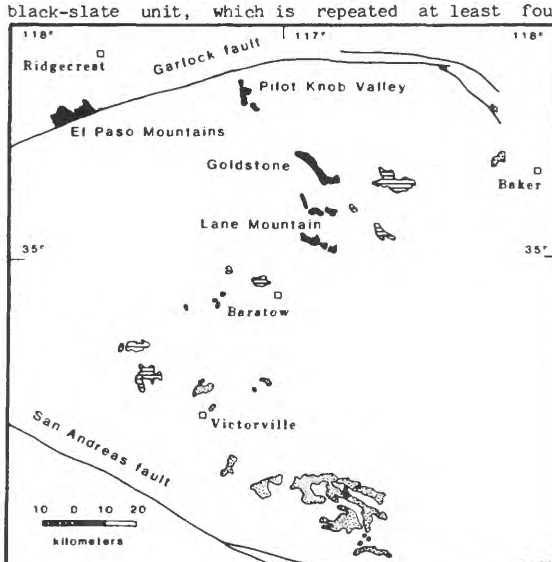

Figure 1. Map of Paleozoic and probable Paleozoic rocks in the western Mojave Desert. Black = eugeosynclinal rocks, dotted = miogeosynclinal and platform rocks, horizontally ruled = probable Paleozoic rocks of unknown paleogeographic origin.

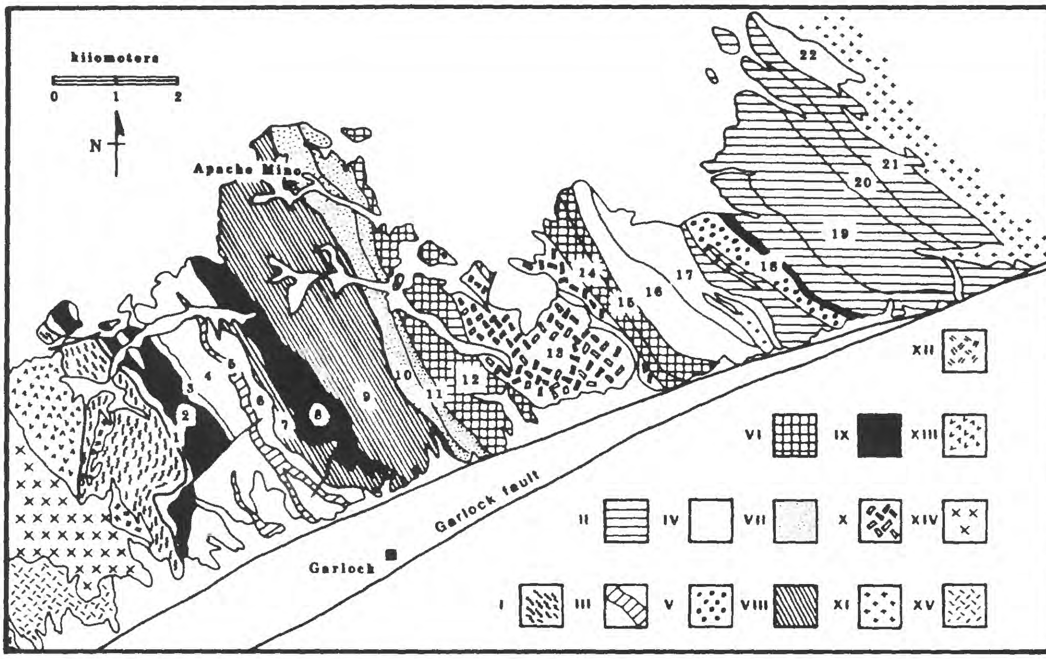

Figure 2. Simplified map of the eastern El Paso Mountains showing the units of Dibblee (1967) and age assignments of this paper. Arabic numerals = Dibblee's units of Garlock assemblage. Map patterns: I - Mesquite Schist; Garlock assemblage: II - lower Paleozoic rocks in the east part of the Garlock, III - Devonian sandy limestone, IV - unfossiliferous metasedimentary units, V - Pennsylvanian carbonate rocks, VI - Lower Permian rocks, VII - Carboniferous(?) "Antler" flysch, VIII - lower Paleozoic rocks in the west part of the Garlock, IX - greenstone; Igneous rocks: X - andesite prophyry, XI - tonalite, XII - trondhjemite, XIII - gneissic quartz monzonite, XIV - quartz diorite, XV - adamellite. El Paso Mountains located in figure 1.

times in the east part of the range, contains Ordovician graptolites. Middle or Late Ordovician conodonts occur in an adjacent limestone unit. The lower Paleozoic rocks in the eastern part of the Garlock assemblage are considered to be of a different deepwater marine facies than similiar aged rocks in the west, because the eastern sequence contains significantly more carbonate rocks.

Upper Paleozoic rocks are present in the middle part of the Garlock assemblage (Dibblee's units 10-12 and 14-15) and are also infolded with lower Paleozoic rocks in the middle part of Dibblee's unit 18. A flysch-like sequence, consisting of quartz-pebble conglomerate, sandstone, and argillite (Dibblee's units 10-11), which Poole (1974) tentatively correlated with the Carboniferous Antler foreland basin sequence of Nevada, overlies Ordovician argillite of the western lower Paleozoic sequence in an apparently faulted unconformity at the Apache mine, in the central part of the range. Overlying the flysch sequence, is a succession of Permian strata (Dibblee's unit 12), which is repeated farther to the east (units 14-15) by faulting and folding. The Permian strata consist of 1) a basal unit of intercalated chert and limestone-pebble conglomerate, skeletal limestone, argillite and siltite, dolomite, and sandstone, 2) an overlying unit of skeletal limestone turbidites interlayered with argillite, and 3) an upper unit of feldspathic sandstone and conglomerate turbidites that contain volcanic rock fragments and are interlayered with argillite. In some places, the feldspathic sandstone turbidite unit is overlain by fine-grained carbonate turbidites interlayered with argillite.

Contacts within the Permian sequence appear to be conformable, but shearing obscures the basal contact so that the relation with the underlying Carboniferous(?) flysch sequence is unknown.

Late Wolfcampian or early Leonardian fusulinids have been collected from the basal Permian unit. Leonardian conodonts occur in the skeletal limestone turbidites, and latest Leonardian conodonts were found several meters above the contact between the skeletal limestone and the feldspathic turbidites.

Lower Permian turbidite sedimentation in the Garlock assemblage reflects a sediment source on the upper Paleozoic continental shelf, but deposition was in deep water as indicated by Nereites-ichnofacies fossils found in the intercalated argillite. A shift in provenance to an unknown volcanic source terrane is indicated by latest Leonardian strata. Following the influx of volcanogenic turbidites, sedimentation of turbidites derived from a carbonate shelf source resumed locally to form an upward-fining sequence.

Pennsylvanian rocks unconformably overlie and are complexly infolded with lower Paleozoic rocks of the eastern sequence near the middle of Dibblee's unit 18. Approximately 20 m of interbedded limestone and chert-cobble conglomerate and calcarenite, including a basal conglomerate that contains clasts of the underlying brown argillite, immediately overlie the unconformity. Thin beds of radiolarian chert are locally interbedded with the limestone. Early to Middle Pennsylvanian conodonts were collected from the bottom of this basal unit, and Middle to earliest Late Pennsylvanian conodonts were collected from the top. Conformably overlying the basal unit are approximately

40 m of thin- to medium-bedded limestone and silty limestone, from which a poorly preserved but diverse fauna of upper Paleozoic marine megafossils was collected, including bryozoans, gastropods, bivalves, articulated crinoid columnals, and fusulinids. This faunal assemblage suggests that these Pennsylvanian rocks were deposited in shallower water than the Carboniferous(?) and Permian rocks farther to the west. An unfossiliferous light-gray slate overlies the limestone with apparent conformity and is, in turn, overlain structurally by greenstone and the repeated eastern lower Paleozoic metasedimentary sequence. The age of the slate is presently unknown, as are the ages of Dibblee's units not discussed above.

In summary, the Garlock assemblage is a tectonically shuffled and diverse assemblage of eugeosynclinal rocks of many ages spanning most of Paleozoic time. Most of the assemblage comprises lower Paleozoic rocks representing two different deepwater marine facies--a probable continental-rise facies in the west and a slightly shallower-water facies that may represent upper continental rise or lower slope to the east. The juxtaposition of these two facies was probably the result of pre-Carboniferous deformation, but the evidence for this event is not conclusive. Upper Paleozoic rocks of varying ages and depositional environments unconformably overlie the lower Paleozoic rocks locally. The entire assemblage was intensly deformed, infolded, and metamorphosed in Late Permian to early Mesozoic time. The assemblage is not a coherent lithostratigraphic sequence and does not constitute a valid formation.

CORRELATIONS

The Garlock assemblage is, in part, correlative with rocks of the Antler allochthon, foreland basin and overlap assemblages of Nevada. Ages and lithologic assemblages are broadly similar.

Tentative lithologic correlations have also been made between the Garlock Formation and assemblages of eugeosynclinal rocks to the south of the Garlock fault in the western Mojave Desert (fig. 1; Smith and Ketner, 1970; Miller and others, 1979). An assemblage of rocks similiar to the western sequence of lower Paleozoic rocks in the Garlock assemblage (fig. 2) is present 60 km east of the El Paso Mountains and 2 km south of the Garlock fault in the Pilot Knob Valley (fig. 1; Smith and Ketner, 1970). Our discovery there of Devonian conodonts in a distinctinve sandy limestone unit, identical to Dibblee's unit 5 of the Garlock assemblage, which also contains Devonian fossils, supports the lithologic correlation by Smith and Ketner (1970) of the Pilot Knob Valley assemblage with the Garlock assemblage. A rock assemblage in the area of Goldstone, California (Miller and Carr, unpublished mapping) is, in part, lithologically and structurally similiar to the lower Paleozoic sequence that contains Ordovician fossils in the east part of the Garlock assemblage. We have found Ordovician graptolites in an interbedded black slate and quartzite in the Goldstone assemblage to support this correlation. Some of the units of the Goldstone assemblage are present also in the Lane Mountain quadrangle to the south, mapped by McCulloh (1960).

The part of the rock assemblage in the Lane Mountain quadrangle that is similiar to rocks at Goldstone and to rocks in the eastern El Paso Mountains have yielded no fossils. However, a second assemblage of rocks in the Lane Mountain area has poorly preserved fusulinids (Rich, 1971; present study) and is, in part, lithologically similiar to the upper Paleozoic rocks in the El Paso Mountains. McCulloh (1954) previously suggested a late Paleozoic age for this part of the Lane Mountain assemblage based on early collections of poorly preserved fossils. To our knowledge, the presence of western facies rocks has not yet been conclusively demonstrated south of the Lane Mountain quadrangle. This point must be carefully considered in evaluating tectonic models that have been proposed for the southern Cordillera.

BIBLIOGRAPHY

Christiansen, R.L., 1961, Structure, metamorphism, and plutonism in the El Paso Mountains, Mojave Desert, California: Stanford University Ph.D. dissertation 180 p.

Cox, B.F. and Morton, J.L., 1980, Late Permian plutonism, El Paso Mountains, California: Geological Society of America Abstracts with Programs, v. 12, no. 3, p. 103.

Dibblee, T.W., Jr., 1952, Geology of the Saltdale quadrangle, California: California Division of Mines and Geology Bulletin 160, 66 p.

Dibblee, T.W., Jr., 1967, Areal geology of the western Mojave Desert, California: U.S. Geological Survey Professional Paper 522, 153 p.

McCulloh, T.H., 1954, Problems of metamorphic and igneous rocks of the Mojave Desert in Jahns, R.E., ed., Geology of Southern California: California Division of Mines and Geology Bulletin 170, p. 13-24.

McCulloh, T.H., 1960, Geologic map of the Lane Mountain quadrangle, California: U.S. Geological Survey open-file report.

Miller, E.L., Burchfiel, B.C., and Carr, M.D., 1979, Enigmatic metasedimentary rocks of the western Mojave Desert, California and their relationship to Cordilleran miogeocline/platform rocks (abs.): Geological Society of America Abstracts with Programs, v. 11, no. 3, p. 92.

Poole, F.G., 1974, Flysch deposits of the Antler foreland basin, western United States in Dickinson, W.R., ed., Tectonics and Sedimentation: Society of Economic Paleontologists and Mineralogists, Special Publication 22, p.58-82.

Poole, F.G., Sandberg, C.A., and Boucot, A.J., 1977, Silurian and Devonian paleogeography of the western United States in Stewart, J.H., Stevens, C.H., and Fritsche, A.E., eds., Paleozoic Paleogeography of the Western United States: Pacific Section, Socitey of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium 1, p. 39-66.

Poole, F.G. and Sandberg, C.A., 1977, Mississippian paleogeography and tectonics of the western United States in Stewart, J.H., Stevens, C.H., and Fritsche, A.E., eds., Paleozoic Paleogeography of the Western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium 1, p. 67-86.

Poole, F.G., and Christiansen, R.L., 1980 , Allochthonous lower and middle Paleozoic eugeosynclinal rocks in the El Paso Mountains, northwestern Mojave Desert, California: Geological Society of America Abstracts with Programs, v. 12, no. 3, p.147.

Rich, M., 1971, Fusulinids from central Mojave Desert and adjoining areas, California: Journal of Paleontology, v. 45, p. 1022-1027.

Smith, G.I. and Ketner, K.B., 1970, Lateral displacement on the Garlock fault, southeastern California, suggested by offset sections of similiar metasedimentary rocks: U.S. Geological Survey Professional Paper 700-D, p. D1-D9.

TECTONIC HISTORY OF THE VIDAL-PARKER REGION, CALIFORNIA AND ARIZONA

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Geologic investigations in the area of the lower Colorado River Valley have provided some new information that permits an integration of part of the geologic history for western Arizona and southeastern California. The studies, aimed principally at evaluating the recency of faulting in the eastern Mojave Desert, were supported by the NRC during evaluation of the region for proposed nuclear power generating facilities.

Rocks of Precambrian, Permian, Cretaceous, Miocene, Pliocene, and Quaternary age have been identified in the Vidal-Parker region. All of the pre-Tertiary rocks have suffered varying degrees of metamorphism. Although some rocks in the Riverside Mountains are probably Precambrian, some evidence suggests that most of the rocks previously mapped in the Vidal-Parker region as Precambrian may be Paleozoic or Mesozoic in age. A section of late Paleozoic rocks, mostly of Permian age, has been recognized in several areas in the region. These rocks are characterized by a uniform fine-grained quartzite that probably correlates, not with the Coconino Sandstone, but with the Esplanade Sandstone of the Supai Group, or the Queantoweap Sandstone of McNair (1951). Differences in the Paleozoic section between the Riverside and nearby Big Maria Mountains, and elsewhere, suggest that major strike-slip faulting may have occurred between those two areas.

One of the most widespread metamorphic rock units is a thick, fairly uniform, partly mylonitic gneiss. This strongly banded or foliated rock occurs above late Paleozoic rocks in several areas, and it is believed to be Mesozoic in age. K-Ar dates and a fission-track age are early Tertiary. These rocks differ in character, however, from other Mesozoic(?) rocks in the region.

Granite grading abruptly into granite gneiss is locally abundant and gives rather consistent late Cretaceous K-Ar ages.

Tertiary rocks of the Vidal-Parker area are Miocene and Pliocene, but nearly all of the volcanic rocks are Miocene. Stratigraphy is highly complex, units are discontinuous, and changes are abrupt. Many pronounced unconformities occur. Breccias and megabreccias are a prominent feature of the stratigraphy. Two major lava sequences, consisting of predominantly rhyodacite and andesite flows and breccias intertongue in the western Whipple Mountains. These rocks range in age from about 22 to 18 m.y. (million years).

Basaltic volcanism began about 15 m.y. ago and continued sporadically for about 10 m.y. Many of the younger mafic lavas are trachybasalts or basaltic andesites. A small center in the Buckskin Mountains erupted trachytes and trachyandesites with peralkaline affinities.

Peach Springs Tuff of Young and Brennan (1974), an important ash-flow tuff stratigraphic marker, has been found at several localities in the Vidal-Parker region. Known localities of the tuff indicate a predominant northeast-southwest distribution, with a possible source southwest of Kingman, Ariz.

Sedimentary material dominates the Tertiary section in most areas, ranging from megabreccia to lacustrine limestone. Megabreccias consist of metamorphic and locally identifiable late Paleozoic rocks. In some areas a prominent unconformity separates volcanic rocks and breccias consisting of granitic and metamorphic rocks from overlying thin-bedded sandstone, siltstone, and limestone.

A detrital unit, called the fanglomerate of Osborne Wash, overlies with sharp unconformity the highly disturbed older Tertiary volcanic and sedimentary rocks. On the basis of dates on intercalated lavas, this unit ranges in age from about 13 to 5 m.y.

The Bouse Formation, a Pliocene estuarine deposit, found at scattered locations below about 330 m, grades upward and laterally into what are interpreted as beach and eolian deposits. The Bouse is generally overlain by deposits laid down by the Colorado River, but in one area fluvial gravels are present beneath the Bouse.

Alluvium in the Vidal-Parker region consists of old highly dissected gravels, intermediate age fan deposits displaying varying degrees of soil and desert varnish formation, and younger alluvium related to present drainage. Ages on these units are imprecise, but the oldest is probably Pliocene and Pleistocene; one of the more prominent intermediate age deposits is apparently about 80,000 years old.

The Vidal-Parker region is a somewhat anomalous part of the Basin and Range physiographic province. It lies within a structural-physiographic belt perceived to be a part of a major continental lineament that extends from Texas to Oregon. In the Vidal-Parker area physiography, geology, and geophysics combine to delineate a northwest-trending zone about 100 km wide, here named the Mojave-Sonoran Belt. This belt can be viewed as a southeastward extension of the Walker Lane of western Nevada. The northeast edge of the belt is marked by a rather abrupt termination of northerly trending basins and ranges; the southwest edge is less distinct, but is defined partly by an en echelon series of northwest-trending faults, commonly expressed topographically, and having important components of strike-slip displacement. Persistent lithologic changes appear to take place along the southwest-belt margin in rocks of Paleozoic and Mesozoic age. Changes in crustal configuration also appear to occur along the boundaries. In the Vidal-Parker region, the belt is also characterized by (1) an almost total lack of seismicity; (2) no surface faulting in intermediate age alluvium, and very minor faulting in rocks younger than about 5 m.y.; (3) only minor faulting since about 13 m.y. ago, although there is evidence that faults are younger and have more displacement toward the boundaries of the Mojave-Sonoran Belt; and (4) a lack of deep alluvium-filled basins. These geologic conditions are reflected in the aeromagnetics and gravity maps as a near absence of pronounced linear gradients or anomalies. The combination of less unmetamorphosed granite in the crust of the Colorado River Valley with a distinct gravity high extending from Yuma to Lake Mead suggests the possibility that the estuary of Bouse Formation time and the course of the Colorado River were influenced by isostatic adjustments.

As a possible result of major strike-slip faulting, the style of pre-Tertiary structure may also change across the boundaries of the Mojave-Sonoran Belt. In the northern Riverside Mountains, the rocks are repeated by reverse faulting semiconcordant with bedding, accompanied by only local appressed folding, plastic deformation and attenuation, which seem to characterize the structure farther to the southwest.

Striking features of the Tertiary deformation of the region are: (1) structural disturbance was restricted to a relatively short length of time, about 22-14 m.y. ago; (2) regionally pervasive northwest-striking, southwest-dipping attitudes in Miocene rocks, and abrupt truncation of these highly deformed rocks by nearly flat-lying fanglomerates and volcanic rocks, mostly of Miocene age; and (3) a lack of deep structural troughs common elsewhere in the Basin and Range.

Lithology and distribution of Tertiary rocks suggest abrupt uplifts along northeast trends followed by regional extension along curving low-angle faults joining a surface of widespread dislocation. The latter feature, here called the Whipple Mountains detachment fault, spans the Mojave-Sonoran Belt and is the master feature of late Cenozoic tectonism. It developed rapidly about 15 m.y. ago and the upper plate moved relatively northeastward, probably more than 20 km. Structure in the upper plate, though locally highly complex, is basically a series of low-angle basin-range type faults that formed contemporaneously to accommodate the extension. Tertiary mineralization appears to have a spatial relation to the fault.

The direct cause of the Whipple Mountains detachment fault is not known, but the consistency of style and movement suggests at least a regional and probably a plate tectonics mechanism, and possibly a plastically extending substratum. It may not be coincidental that initiation of Miocene movement on the San Andreas fault and ending of displacement on the Whipple Mountains detachment fault both occurred about 14 m.y. ago. It is suggested that the relatively early end of late Cenozoic faulting in the Vidal-Parker region may be a result of anomalously shallow depth of the boundary between plastic and brittle crustal failure, so that during about the last 10 m.y., extension has taken place, but almost entirely by plastic flow.

Plio-Pleistocene tectonic features in the region are limited to a few faults, mostly with a few meters of displacement, except at the northeast edge of the area where several faults may have significant Pliocene displacement. A few small faults are known to cut the Bouse Formation, and a persistent zone of small faults occurs northwest of Parker in beds possibly as young as the older alluvium. About a dozen such small faults, fault zones, or lineaments were found in the region. Only local slight warping appears to have occurred in Pleistocene and Holocene time.

MECHANICS OF FAULT DEFORMATION AND SEISMOTECTONIC ZONING
MOJAVE DESERT, CALIFORNIA

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Theoretical mechanics provides a basis for describing and predicting stress distributions and deformation. A model based on theory of plasticity (modified Prandtl cell) was used by Cummings (1976) to describe the stress distribution and fault deformation in the Mojave desert. That theoretical model has been modified (Cummings, 1981) to more precisely correspond to the boundary conditions defined by field observations; specifically, the Garlock fault has been modelled to better approximate its change in strike.

The modified Prandtl cell mathematically predicts: (1) the preferential development of the northwest-trending strike slip faults and the correct sense of relative movement along them, (2) the concave-east and convex-east distortion of the northwest trending faults, (3) the east-west trending strike slip faults and the correct sense of relative movement along them without changing the boundary conditions, and (4) the correct range of strike-slip displacement on the northwest-trending faults ($\lesssim$ 10 km) (Cummings, 1976). By the change in the boundary conditions (Cummings, 1981), the mathematical model additionally predicts larger values of shear stress in the eastern half of the Mojave desert with the consequence that faults and earthquakes have a greater potential for developing there compared to the western half. By incorporating the asymmetry of stress produced by the greater movement along the San Andreas fault, the larger values of shear stress within the Mojave wedge are shifted northward, with corresponding changes in the distribution of earthquakes. All these predictions are remarkably consistent with field observations. The apparent success of the model in describing stress distributions and locations of earthquakes and faults has led to a map by Cummings (1981) describing seismotectonic zones.

A model has been proposed, based on theory of elasticity (Garfunkel, 1974), to explain the fault pattern and distribution in the Mojave. Many of the assumptions and conclusions of this model are not consistent with the known geologic conditions. A few of the deficiencies of this model are: (1) inability to explain rigorously the preferential development of northwest trending faults, (2) inability to explain the east-west strike-slip faults in the northeastern part of the area, (3) inability to explain concavity and convexity of the northwest-trending faults, (4) inability to explain why these northwest-trending faults are preferentially restricted to the eastern Mojave, and (5) inconsistency of predicted values of lateral displacement along these faults with observed values. Predicted lateral displacements are considerably larger (up to a factor of 10) than those reported by Miller (1980) and by field measurements (Dokka, 1979). His model is also restricted because it cannot be used to predict stress distributions that would produce the observed strain.

REFERENCES CITED

Cummings, David, 1976. Theory of plasticity applied to faulting, Mojave Desert, southern California: Geol. Soc. Amer. Bull., V.87, p 720-724.

______________, 1981. Mechanics of fault deformation and seismotectonic zoning, Mojave Desert area, California: in Geology and Mineral Wealth of the Mojave Desert Area, California, Spec. Pub., South Coast Geol. Soc.

Garfunkel, Z., 1974, Model for the late Cenozoic tectonic history of the Mojave Desert, California, and for its relation to adjacent areas: Geol. Soc. Amer. Bull., V. 85, p 1931-1944.

Dokka, R.K., 1979. Styles and timing of late Cenozoic faulting, central Mojave Desert, California (abs): Geol. Soc. Amer. Abstr. Programs, V. 11, No. 7, p 414.

Miller, S.T., 1980. Geology and mammalian biostratigraphy of a part of the Northern Cady Mountains, Mojave Desert, California: U.S.G.S. Open File Report 80-878.

INTERACTION OF PLUTONISM, METAMORPHISM, AND THRUST FAULTING IN A SEGMENT OF THE CORDILLERA DURING THE MESOZOIC.

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The cause and effect relations among plutonism, metamorphism, and thrust faulting within the southern portion of the Cordillera are evaluated with the aid of tectonic cross-sectional reconstructions along latitude 36°N from Las Vegas to the California Coast Ranges. Significantly different plate tectonic processes were apparently controlling the structural evolution of the Cordillera at 180, 150, and 120 m.y. Following a relatively straightforward subduction-dominated regime at 180 m.y. (Saleeby and others, 1979; Dunne and others, 1978), crustal extension and active marginal basin formation (Fig. 1) were imposed at 150 m.y. (Chen and Moore, 1978; Bailey and others, 1964; Lanphere, 1971; DeWitt and others, 1979). By 120 m.y. east-directed subduction of oceanic crust beneath an Andean-type margin (Chen, 1978; Burchfiel and Davis, 1975; Davis and others, 1978) typfied the southern Cordillera.

Plutonism, which is assumed to be directly related to subduction of oceanic mantle, has been nearly continuous from 180 to 120 m.y., with the exception of a real gap from 150 to 135 m.y. Cooling within metamorphic terrains that lie to the east of the plutonic arc began ≳150 m.y., but was protracted to ~90 m.y. Thrust faulting within the wedge of sedimentary rocks that lie east of the plutonic arc began ≥ 180 m.y. and persisted until at least 120 m.y., if not later. The change from a compressive, subduction-related mode at 180 m.y. to an extensional, back-arc spreading regime at 150 m.y. controlled formation of the Franciscan and Great Valley sedimentary wedges, emplacement of the Independence Dike swarm, and cooling of the metamorphic terrains. Considering all available data, the following tectonic history is proposed.

Subduction of oceanic mantle beneath the Cordilleran margin has controlled, as a first-order effect, the development of extensive plutonic arcs. Metamorphic terrains formed to the east of the plutonic arc are a second-order phenomena also controlled by subduction. They possibly form as a response to deep-seated partial melting when magmas rise within the continental mantle, but do not reach upper crustal levels. Extensive heating of the mantle and crust beneath the metamorphic terrains creates a thermally weakened zone, within which continental crust is temporarily subducted. A significant portion of the foreland fold and thrust fault belt may be formed by this process, wherein thrust faulting is controlled more by the localization of metamorphic terrains than plutonic complexes. Subduction geometries and events apparently control many processes in an evolving active continental margin.

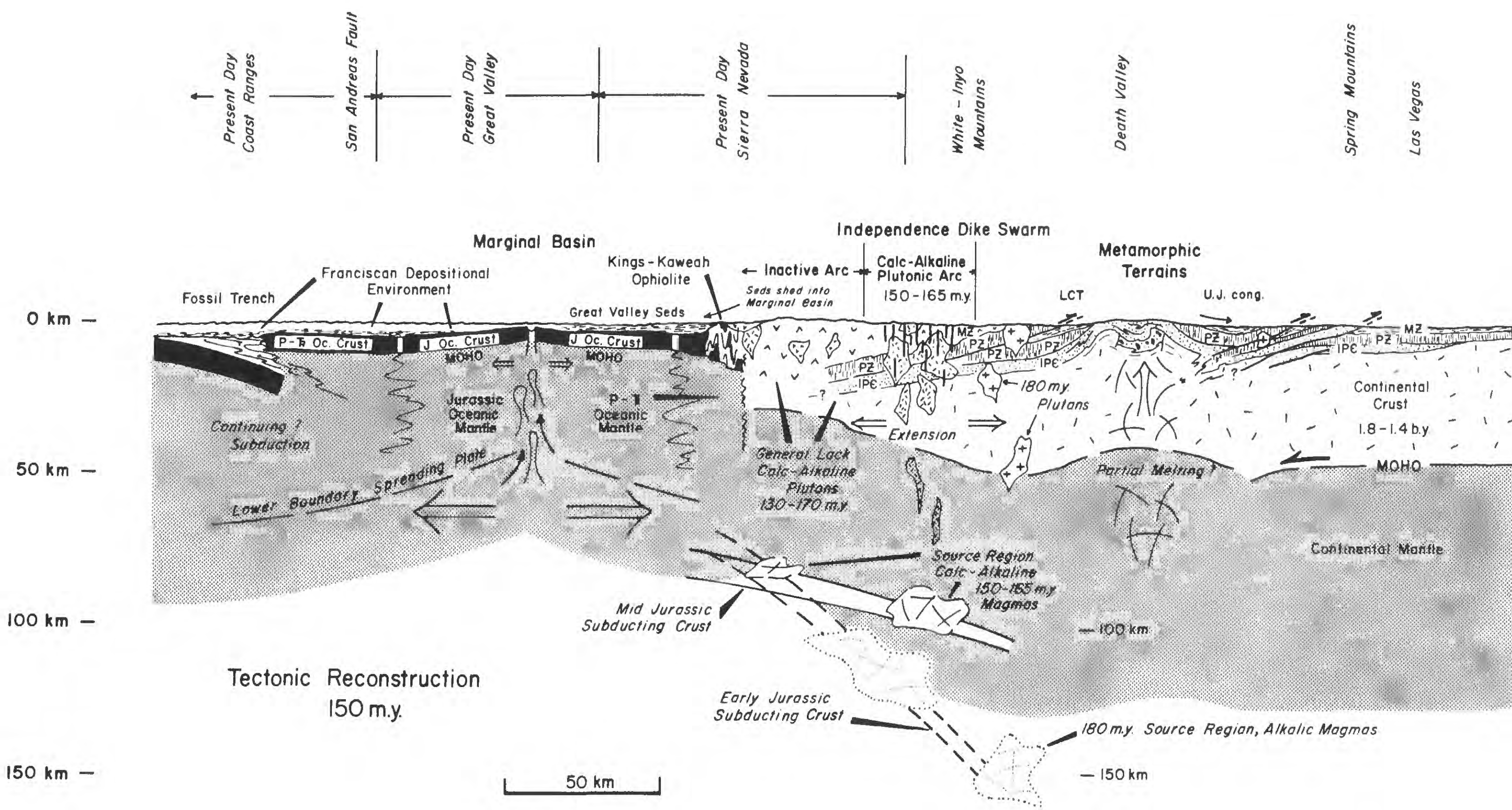
Present Day
Coast Ranges
San Andreas Fault
Present Day
Great Valley
Present Day
Sierra Nevada
White - Inyo
Mountains
Death Valley
Spring Mountains
Las Vegas
Marginal Basin
Independence Dike Swarm
Metamorphic
Terrains
Fossil Trench
Franciscan Depositional
Environment
Kings-Kaweah
Ophiolite
Great Valley Seds
← Inactive Arc →
Seds shed into
Marginal Basin
Calc-Alkaline
Plutonic Arc
150-165 m.y.
LCT
U.J. cong.
P-Tr Oc. Crust
J Oc. Crust
J Oc. Crust
MOHO
MOHO
Jurassic
Oceanic
Mantle
P-Tr
Oceanic
Mantle
Continuing ?
Subduction
Lower Boundary Spreading plate
MZ
PZ
IPC
180 m.y.
Plutons
Extension
General Lack
Calc-Alkaline
Plutons
130-170 m.y.
Continental
Crust
1.8-1.4 b.y.
MOHO
Partial Melting ?
Continental Mantle
Source Region
Calc-Alkaline
150-165 m.y.
Magmas
Mid Jurassic
Subducting Crust
— 100 km
Early Jurassic
Subducting Crust
180 m.y. Source Region, Alkalic Magmas
— 150 km
0 km
50 km
100 km
150 km
50 km
Tectonic Reconstruction
150 m.y.

Figure 1

References

Bailey, E. H., Irwin, W. P., and Jones, D. L., 1964. Franciscan and Related Rocks, and their significance in the Geology of Western California: in California Division of Mines and Geology Bull. 183, 177 p.

Burchfiel, B. C. and Davis, G. A., 1975. Nature and controls of Cordilleran orogenesis, western United States: Extensions of an earlier synthesis: Am. Jour. Sci., v. 275-A, p. 363-396.

Chen, J. H., 1978. Age and origin of the Sierra Nevada Batholith, California: U. S. Geol. Survey Open File Rept. 78-701, p. 65-66.

Chen, James H. and Moore, James G., 1979. Late Jurassic Independence dike swarm in eastern California: Geology, v. 7, p. 129-133.

Davis, G. A., Monger, J. W. H., and Burchfiel, B. C., 1978. Mesozoic Construction of the Cordilleran "Collage," Central British Columbia to Central California: in Mesozoic Paleogeography of the Western United States. Howell, D. G. and McDougall, K. A., eds., Pac. Coast Paleogeography Symposium II. Pacific Section, Soc. Econ. Paleont. and Mineral., p. 1-32.

DeWitt, Ed, Armstrong, R. L., Sutter, J. F., and Zartman, R. E., 1979a. Isotopic systematics in a metamorphosed granitic terrain, southeast California. (Abst): EOS, v. 60, no. 18, p. 425.

Dunne, George C., Gulliver, R. M., and Sylvester, A. G., 1978. Mesozoic evolution of rocks of the White, Inyo, Argus and Slate Ranges, eastern California: in Howell, D. G. and McDougall, D., eds., Mesozoic paleogeography of the western United States. Soc. Econ. Paleontologists and Mineralogists, Pacific sec., Pacific Coast Paleogeography Symposium II, p. 189-207.

Lanphere, M. A., 1971. Age of the Mesozoic Oceanic Crust in the California Coast Ranges. Geol. Soc. America 82, 3213-3220.

Saleeby, J. B., Mattinson, J. M., and Wright, J. E., 1979. Regional Ophiolite Terrances of California-Vestiges of Two Complex Ocean Floor Assemblages: Geol. Soc. Amer. abstracts with programs, v. 11, no. 7, p. 509.

REGIONAL STRUCTURE OF THE MOJAVE DESERT

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In the Mojave Desert, the Paleozoic and Mesozoic marine sedimentary series deposited in the deeply subsided Cordilleran geosyncline rests on a platform of Pre-Cambrian gneissic and plutonic rocks. This sedimentary series was affected, primarily during the Mesozoic Nevadan and Laramide orogenies, by complex folding on primarily north trending axes, by low angle east or west dipping thrust faults, and by high angle faults. In the central and western Mojave Desert, these complexly deformed sediments are locally intruded and overlain by Mesozoic andesitic volcanic rocks, are moderately metamorphosed, and intruded by Mesozoic plutonic rocks. The plutonic intrusions destroyed all but small pendants of the metamorphic rocks and form the southeastern extension of the Sierra Nevada batholith. In the desert region, this batholith includes many rock types, but quartz monzonite predominates. The batholith is composed of several generations of granitic rocks with the older ones locally cut by hypabyssal dike swarms.

All of the rocks mentioned above collectively form the basement complex, which reacted to Cenozoic stresses as a solid crystalline mass. They constitute the platform upon which Cenozoic terrestrial volcanic and sedimentary deposits rest. During the Cenozoic Era, the Mojave Desert tectonic province became outlined as a wedge-shaped block between the San Andreas and Garlock faults (Fig. 1). This terrain eventually became isolated from the Pacific marine area to the west by uplifts along the San Andreas fault zone and by the Sierra Nevada uplift north of the Garlock fault. Although the Mojave block has no definite eastern boundary, the Soda-Avawatz fault zone (Fig. 1) appears to separate mountain ranges of different trends.

During early Tertiary time much, if not all, of the basement terrain of the Mojave block was probably mountainous, but by middle Tertiary (Oligocene-Miocene) time it had been further affected by crustal movements and volcanic eruptions. Parts of this terrain were re-elevated to form highlands while other parts were depressed to form undrained valleys. The valleys formed as trough-like basins with axes trending predominantly east-west. These include the Cajon, East Antelope and West Antelope basins north of the San Andreas fault, the Kramer and Barstow basins in the central Mojave Desert, and the Mojave and Koehn basins near the Garlock fault (Dibblee, 1967). Basement detritus eroded from the rising highlands and volcanic material, which had erupted mostly from the valley margins, accumulated in the subsiding valleys. In some of the valley basins, the volcanic-sedimentary sequences accumulated to great thicknesses. The sequences range in age from Oligocene to Pliocene.

The Tertiary volcanic-sedimentary sequences in each of these basins were later affected by crustal movements in Pleistocene time when they were, in part, tilted, elevated, and folded along generally east trending axes. The deposits are most severely deformed along and near the San Andreas fault zone and are deformed locally along the Garlock fault and northwest trending faults within the Mojave block. Local deformation is

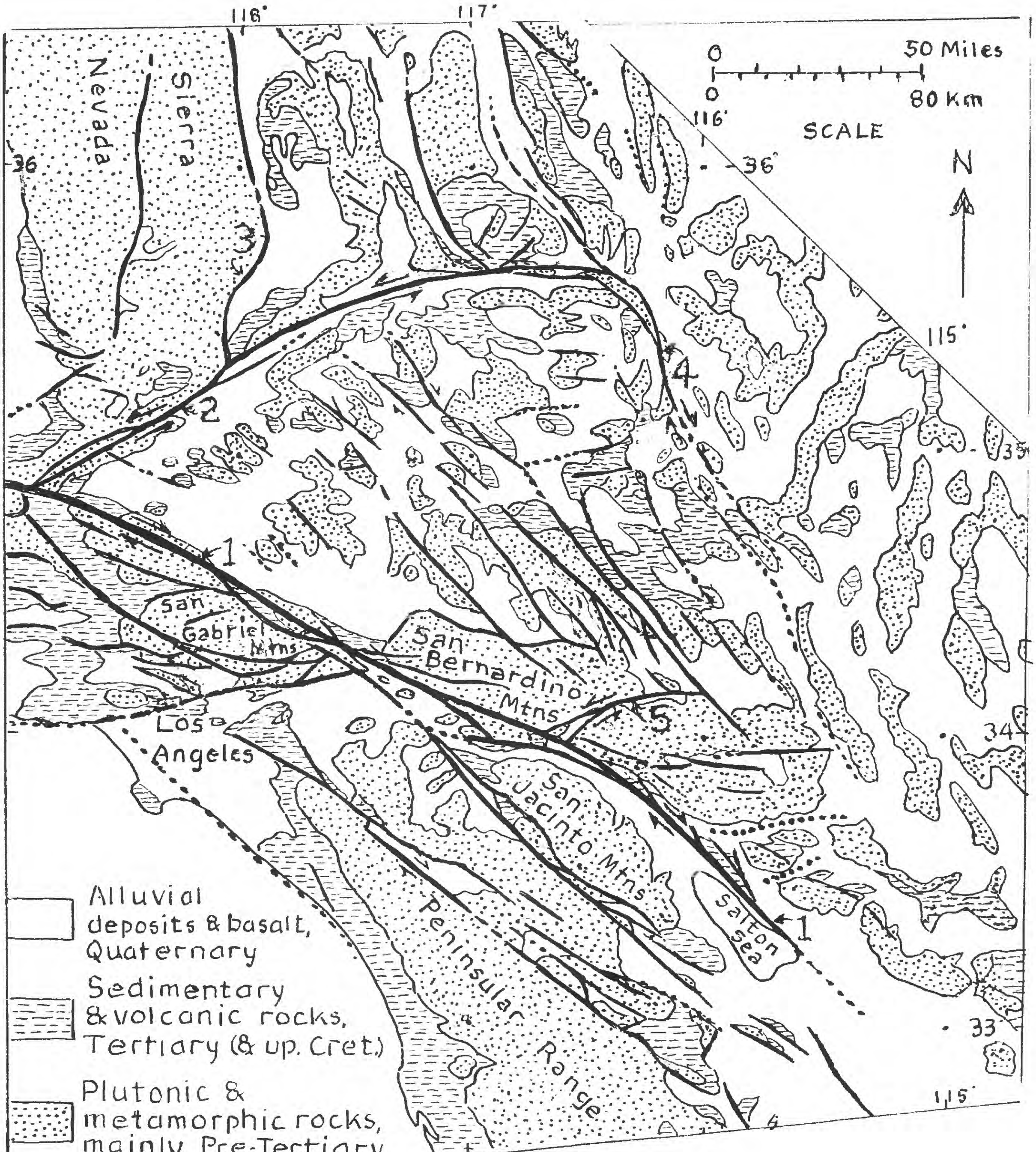

Figure 1. Geologic map of Mojave Desert and adjacent regions showing major high-angle faults and their relations to elevated areas. Some faults as follows: 1,San Andreas; 2,Garlock; 3,Sierra Nevada; 4,Soda-Avawatz; 5,Pinto Mountain.

apparently due to lateral drag movements. In places, the deformed Tertiary formations are unconformably overlain by Pleistocene gravels and basalt flows that in some places are deformed along northwest trending faults.

In the central Mojave Desert, where a very thick Oligo-Miocene volcanic-sedimentary series rests on a very uneven basement surface, the basal contact has been interpreted to be a detachment fault (Dokka, oral communication, 1980), but this interpretation is believed to be erroneous.

The San Andreas and Garlock faults are active vertical faults along which the terrain southwest of the San Andreas moved northwestward and that northwest of the Garlock moved southwestward with respect to the Mojave wedge (Fig. 1). Both faults were active in Quaternary time and probably much, if not all, of late Tertiary time, with by far the greater movement on the San Andreas fault.

The southeastern half of the Mojave block is broken by a number of vertical faults nearly parallel to the San Andreas (Fig. 1) and with similar, but small, right-slip displacements. Southeast of the eastern Garlock fault and southeast of the San Bernardino Mountains, an elevated part of the Mojave block, the desert terrain is broken by several east-trending vertical faults with small left-slip displacements as on the Garlock fault. Most of the vertical strike-slip faults within the Mojave block cut Quaternary formations and are active or potentially active.

From this fault pattern within the Mojave block, it is evident that two sets of high-angle strike-slip faults prevail as previously recognized (Hill and Dibblee, 1953; Garfunkel, 1973). The dominant set is the longitudinal set of northwest trending right-slip faults of the San Andreas fault system. The subordinate set is the transverse set of east to northeast trending left-slip faults of which the Garlock fault is the largest. Some of the transverse faults intersect the longitudinal faults but do not cross them. Where they intersect, the terrain at the obtuse angle made by the intersection has been elevated into mountains by compression that presumably resulted from the impidement of strike-slip movement on both faults. Prime examples are uplift of the Tehachapi and San Bernardino Mountains where the San Andreas fault is intersected by the Garlock and Pinto Mountain faults respectively, and the Avawatz Mountains at the intersection of the Garlock and Soda-Avawatz faults. The terrain at the acute angle of each intersection is commonly depressed, apparently by pull-apart tension, as at the intersection of the San Andreas and the Garlock fault.

REFERENCES

Dibblee, T. W. Jr., 1967, Areal geology of the western Mojave Desert, California: U. S. Geological Survey Professional Paper 522.

Garfunkel, Z., 1974, Model for late Cenozoic tectonic history of the Mojave Desert, California, and its relation to adjacent regions: Geological Society of America Bulletin, v. 85, p. 1931-1944.

Hill, M. L. and Dibblee, T. W. Jr., 1953, San Andreas, Garlock and Big Pine faults, California, a study of the character, history and tectonic significance of their displacement: Geological Society of America Bulletin, v. 64, p. 443-458.

EARLY MIOCENE DETACHMENT FAULTING IN THE CENTRAL MOJAVE DESERT, CALIFORNIA

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Recently completed field studies in the central Mojave Desert of California (Fig.1) have documented the occurrence of a regionally developed thin-skinned extensional fault complex (Dokka, 1979, 1980). The proximal portion of this early Miocene terrane is spectacularly exposed in the Newberry Mountains where it is characterized by a brittly distended upper plate that overlies a relatively underformed crystalline basement. The boundary between these two zones is a low-angle surface of detachment, herein referred to as the Newberry Mountains detachment fault (NMDF). Field reconnaissance has shown that structural elements exposed in the Newberry Mountains have counterparts to the east and north in the Rodman, Cady, and Bullion Mountains, implying a surface exposure or at least 4,500 km^2.

Rocks of the Newberry Mountains and surrounding environs are separable into groups on the basis of their structural position relative to the NMDF and include: 1) lower plate 2) upper plate; and 3) syn-kinematic deposits. Lower plate rocks consist of pendants of metasedimentary and metavolcanic rocks embedded in a Mesozoic granitic batholith. Metamorphism of the metasediments (marble, calc-silicate, and gneiss) resulted from the high grade metamorphic conditions produced during the emplacement of the batholith. Pre-batholithic andesite-dacite, correlative with the Sidewinder Volcanic Series, occurs discontinuously throughout the area as a complex pile of weakly metamorphosed flows, tuffs, and intrusives. Rocks of the batholith vary in composition from granite to quartz diorite. Along the NMDF to depths to 100m, these rocks are highly shattered and cataclasized, forming a coherent microbreccia. Upper plate rocks consist of ~6,750m of lower Miocene volcanics (basalt, andesite, dacite, and tuff) and coarse alluvial fan deposits (breccia, conglomerate) consisting of volcanic, granitic and metamorphic basement clasts. Syn-kinematic rocks consist of thick wedge-like deposits of monolithologic basement-derived breccias and conglomerates that are areally restricted to the perimeter of the extended terrane.

Extension of the upper plate was accomplished along high-angle normal faults that merged with the flat NMDF at a (2-7 km) shallow level. Lack of upper plate lower Miocene strata in lower plate positions and occurrence of petrologically similar basement rocks above and below the NMDF indicate that detachment occurred <u>within</u> the basement. Tilting of originally horizontal strata was accomplished by simultaneous block rotation and faulting on multiple, subparallel, high-angle faults. Figure 2 depicts the geometric development of this terrane by way of series of cross-sections.

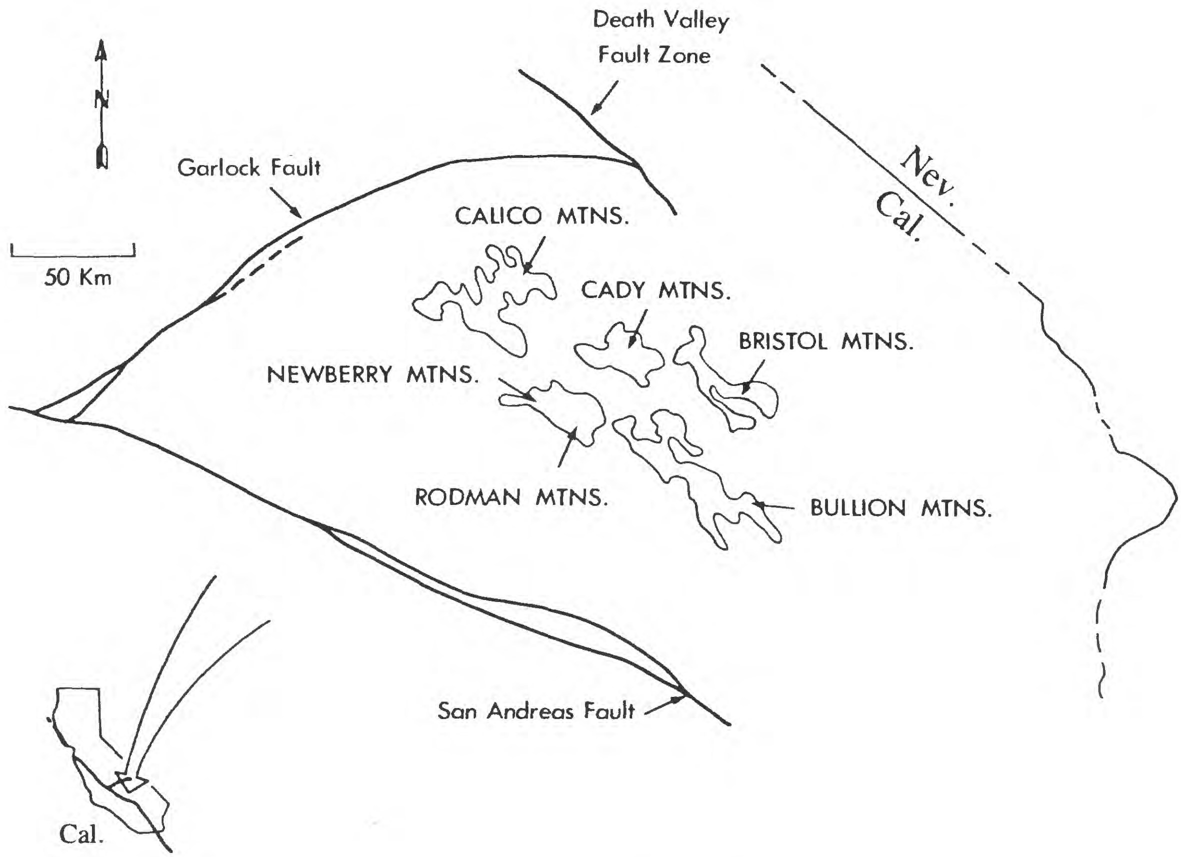

Figure 1—Index Map to Localities in the Central Mojave Desert

To the west and south, the extensional complex abruptly terminates against regions of no apparent extension along the upturned margin of the NMDF (locally called the Kane Springs fault). The curviplanar geometry of the basal detachment at its margin resulted in tilting and foundering of the edge of the upper plate (by reverse drag) and the development of a structural trough along the concave side of the fault as the terrane extended. Growth fault relations occur along the perimeter of the terrane.

Kinematic indicators such as striations on slickensided surfaces on faults, sense and direction of rotation of upper plate strata, and the strike of intra-terrane tear faults strongly suggest that the transport was to the northeast (N51E). The time of detachment faulting in the Newberry Mountains is tightly constrained by the primary age of the deformed rocks (tilted upper plate strata; 23.1 + 2 m.y., Nason and others, 1979) and the age of the overlying post-kinematic sediments (flat-lying; 21.0 + 1.0 m.y., Dokka 1980).

(A)

(B)

(C)

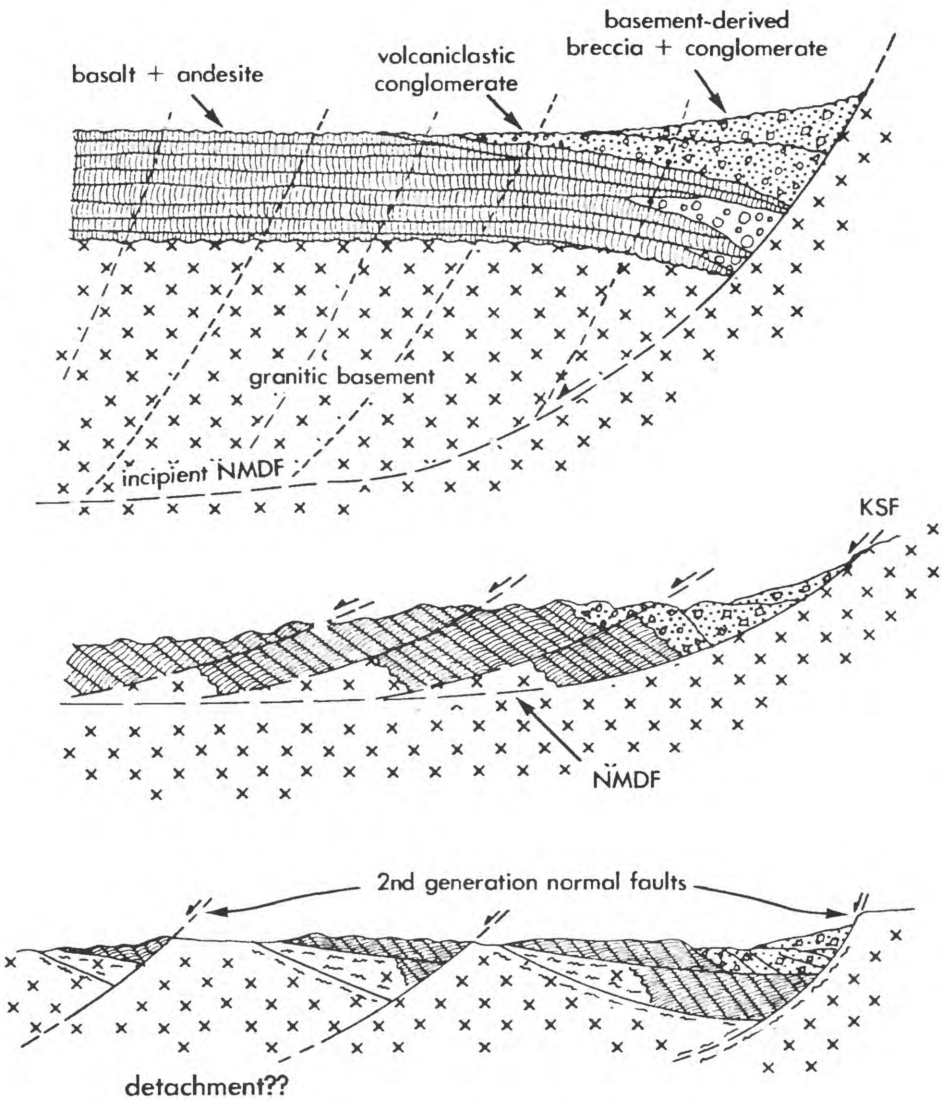

Figure 2—Developmental Model for Upper Plate Extension in the Newberry Mountains (A) incipient extension (B) detachment and rotation and shuffling of upper plate rocks (C) second phase normal faulting and rotation

MID-TERTIARY EXTENSIONAL OROGENY OF SOUTHWESTERN NEW MEXICO AND OTHER PARTS OF THE BASIN AND RANGE PROVINCE

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Southwestern New Mexico is part of the mid-Tertiary volcanic province which covers $10^6 km^2$ of western Mexico and the southwestern U.S. to average depths > 1 km. This province largely, but imperfectly, coincides with the Basin and Range province. Work in New Mexico has resulted in the following conclusions:

1. Mid-Tertiary volcanism began about 40 m.y. ago with eruptions from andesitic stratovolcanoes. By 35 m.y., quartz latitic ash-flow tuffs began to erupt from cauldrons situated at apices of plutons.
2. Between about 30 and 20 m.y., compositions of andesitic lavas and siliceous ash-flow tuffs increasingly diverged; andesitic rocks became more mafic and ash-flow tuffs more siliceous. However, there was no sharp chemical break between early andesites and later "basaltic andesites," which continued to follow calc-alkalic trends. Similarly, no sharp chemical break separates early quartz latite and late high-silica rhyolite ash-flow tuffs, although distinct magma pulses can be recognized in the field (Bornhorst, 1980).
3. Geochemical evidence suggests that andesitic magma formed by partial hydrous melting of mantle peridotite at 50-100 km. Increasingly mafic composition suggests progressively deeper and/or depleted melt zones. Siliceous magma may have formed by partial melting of lower crustal gneiss and granulite at 20-40 km, from progressively higher and more siliceous melt zones. Isotope and trace-element geochemistry is inconsistent with partial melting of subducted oceanic lithosphere (Lipman and others, 1978; Bornhorst, 1980), although water from a dehydrating slab could have played a role in early stages.

By cautious extrapolation to the entire Basin and Range province, further conclusions can be drawn:

1. Regional chemical trends suggest a correlation of K_2O at 60% SiO_2 (data from Lipman and others, 1972) with crustal thickness (Smith, 1978). No compelling evidence links K_2O to depth of subducted slab(s).
2. Extension seems to have occurred in two stages: the first coincided with the culmination of siliceous volcanism and was characterized by structures related to major ductile extension (low-angle normal faults, late stages in emplacement of core complexes) and cauldron collapse. The second stage, post-20 m.y., resulted in relatively minor extension and major vertical movements, resulting in present basins and ranges. It was accompanied by truly basaltic or bimodal volcanism. The two stages overlap: old faults were repeatedly reactivated and the ductile regime locally persisted in the most mobile areas (e.g. Rio Grande Valley, Valles Caldera, Long Valley, and, judging from papers in this volume, the Mohave block). However, most throughgoing

faults bordering modern basins and ranges bear little relation to structures of the ductile stage.

Pursuing the suggestion of Scholz and others (1971), it is proposed that the ductile stage of the mid-Tertiary extensional orogeny of western North America is the continental counterpart of the opening of an oceanic back-arc basin, i.e. an aborted attempt to open a "Sea of Japan" between the craton and the marginal mobile belt (Elston and Bornhorst, 1979). Ductile extension continued after the ridge-trench collision at the western plate margin, about 30 m.y. ago, but gradually gave way to the regime which resulted in the modern fault-block physiography.

Back-arc spreading ordinarily occurs when old and cold oceanic lithosphere is being subducted. Where an oceanic back-arc extends into continental lithosphere, an ash-flow tuff province seems to result. The extension of the modern Lau back-arc basin into the Taupo volcanic zone of New Zealand is an example. In the mid-Tertiary of North America, the zone of extension was far wider and the degree of partial melting far greater, perhaps because the near-ridge oceanic lithosphere that was being overridden was young and hot.

The scenario presented here would explain the following observations on southwestern New Mexico:

1. The succession of rock types. The early andesites and quartz latites would represent an Andean arc, broadened by early stages of back-arc extension. At the culmination of ductile extension, diapirs of mantle material, at temperatures near the solidus, rose into lower-pressure zones of the crust; progressively more mafic basaltic andesite was generated by partial melting (plus contamination?). Being several hundred degrees above the solidus for granite-rhyolite, the rising diapirs induced partial melting of the granulitic-gneissic lower crust and generated increasingly siliceous rhyolite from progressively higher levels. This interpretation is consistent with geophysical observations on modern ash-flow tuff centers, e.g. Yellowstone (Eaton and others, 1975) and Long Valley (Bailey and others, 1976).
2. The emplacement of plutons. About 30 major cauldron complexes are in various stages of documentation (in the entire volcanic province of western North America there must be many hundreds). At least one-third of the area is likely to be underlain by mid-Tertiary plutons; where exposed, they are steep-side and were passively emplaced. Massive ductile extension would overcome a serious "room problem."

On a broader scale, the scenario is consistent with extension of the entire Basin and Range province by hundreds of kilometers, as suggested by Wise (1963) and Hamilton and Myers (1966). It would explain the succession of structures from ductile (listric and detachment faults, core complexes) to brittle (high-angle normal faults coeval with alkali basalt) and the geophysical characteristics of the province (thin crust, high heat flow, S_n-wave attenuation, bilateral symmetry of gravity and magnetic patterns of the Great Basin).

REFERENCES

Bailey, R.A., Dalrymple, G.B., Lanphere, M.A., 1976, Volcanism, structure, and geochronology of Long Valley, California: Jour. Geophys. Res, v. 81, p. 725-744.

Bornhorst, T.J., 1980, Major-and trace-element geochemistry and mineralogy of Upper Eocene to Quaternary volcanic rocks of the Mogollon-Datil volcanic field, southwestern New Mexico: Unpub. Ph.D. dissert. Univ. N.Mex., Albuquerque, 2 vols., 1,108 p.

Eaton, G.P., Christiansen, R.L., Iyer, H.M., Mabey, D.R., Blank, H.R., Jr., Zietz, I., and Gettings, M.L., 1975, Magma beneath Yellowstone National Park: Science, v. 188, p. 787-796.

Elston, W.E. and Bornhorst, T.J., 1979, The Rio Grande rift in context of regional post-40 m.y. volcanic and tectonic events, in Rio Grande Rift: Tectonics and Magmatism (R.E. Riecker, ed.): Am. Geophys. Union, p. 416-438.

Hamilton, Warren, and Myers, W.B., 1966, Cenozoic tectonics of the western United States: Rev. Geophysics, v. 4, p. 509-549.

Lipman, P.W., Doe, B.R., Hedge, C.E., and Steven, T.A., 1978, Petrologic evolution of the San Juan volcanic field, southwestern Colorado: Pb and Sr isotopic evidence: Geol. Soc. America Bull., v. 89, p. 59-82.

Lipman, P.W., Prostka, H.J., and Christiansen, R.L., 1972, Cenozoic volcanism and plate-tectonic evolution of the western United States, part 1, Early and Middle Cenozoic: Royal Soc. London Phil. Trans., A, v. 271, p. 217-248.

Scholz, C.H., Barazangi, Muawia, and Sbar, M.L., 1971, Late Cenozoic evolution of the Great Basin, western United States, as an ensialic interarc basin: Geol. Soc. America Bull., v. 82, p. 2979-2990.

Smith, R.B., 1978, Seismicity, crustal structure, and intraplate tectonics of the interior of the western Cordillera: Geol. Soc. America Mem. 152, p. 111-144.

Wise, D.U., 1963, An outrageous hypothesis for the tectonic pattern of the North American Cordillera: Geol. Soc. America Bull., v. 74, p. 357-362.

MESOZOIC AND CENOZOIC DEFORMATION AND IGNEOUS ACTIVITY IN THE LITTLE MARIA MOUNTAINS, RIVERSIDE COUNTY, CALIFORNIA.

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The Little Maria Mountains form a complex northwest-trending range within Riverside County, California. Highly deformed and moderately metamorphosed (middle to upper greenschist grade) Paleozoic cratonal strata, correlative with the Grand Canyon sequence, and Mesozoic metasedimentary rocks overlie a Precambrian granitic and gneissic basement. These rocks were deformed and perhaps remobilized during Mesozoic times. Igneous rocks related to three separate intrusive events invade both the metasedimentary rocks and the basement complex. A Jurassic pluton of granodioritic composition which is characterized by large feldspar phenocrysts intrudes the west-central Little Maria Mountains. Further northward, the range is intruded by a series of dioritic dikes and sills and a leucocratic quartz monzonite pluton of 80 and 55 million years old, respectively. Large-scale recumbent folds trend roughly east-west and are most evident in the Paleozoic metasedimentary section. Despite extreme thickening and thinning of strata, formational boundaries remain surprisingly intact. A Hansen fold analysis was conducted in two locations in the Little Maria Mountains within the Mauv Formation, a Cambrian metasedimentary unit consisting largely of calcite and dolomitic marbles, locally inter-layered with chert. The resulting slip lines, or direction of transport, trend roughly north-south with a shallow northerly plunge. Tight clustering of data points suggests one continuous deformation is responsible for all the folding in the Little Maria Mountains. Large-scale patterns of folding show south-southwest vergence which is similar to that of the Big Maria Mountains to the south. All units are offset by high-angle, northwest-trending faults that have both normal and right-lateral movement which are probably correlative with those described by Warren Hamilton (1971) in the Big Maria Mountains. Late Mesozoic plate convergence and north-to northeast-directed underthrusting are the probable cause of the principal deformation present in the Little Maria Mountains. This deformation seems correlative to that found in the Palen Pass area to the west (R. Demaree, pers, commun., 1980) and the Big Maria Mountains area to the southeast (M. J. Ellis, pers. commun., 1980).

CRUSTAL STRUCTURE OF THE MOJAVE DESERT, CALIF.

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Seismic-refraction profiles and geophysical studies in wells (<1 km deep) have begun to shed light on relatively shallow crustal structure in the Mojave Desert, California. Deep (>10 km) structure cannot be fully understood without understanding shallow structure, but inferences can be made. From shallow to deep, the known and inferred crustal structure of the Mojave Desert is as follows:

1) Scattered alluvial basins as deep as 0.4 km are seen along a seismic-refraction profile from Rogers Dry Lake, in the western Mojave Desert, to Holcomb Ridge, in the San Andreas fault zone to the south (see index map in fig. 1). Sedimentary velocities range from 1.6 to about 2 km/s. An alluvial basin underlying nearby Rosamond Dry Lake is apparently more than 2 km deep, based on an interpretation of gravity data (Ponti, 1980).

2) Granitic rocks exposed at the surface and underlying the alluvial basins can be modeled in two parts: a) an upper part 0.5 to about 3 km thick where velocity increases relatively rapidly with depth from 4.8 to 5.8 km/s; and b) a lower part where the velocity increases relatively slowly from 5.8 to at least 6.2 km/s at 10 km depth (fig. 1). Mapping of cracks in wells together with velocity logging and laboratory velocity studies indicate that the upper part of the granitic rocks is a region where cracks are closing rapidly with depth, and the lower part is a region where cracks are largely closed (Dan Moos, written commun., 1981).

3) There is weak evidence for an intermediate crustal layer with a velocity of 6.8 to 7.0 km/s at about 20 km depth at least in the region southwest of Lake Mead, Nevada (Roller and Healy, 1963).

4) Mantle apparent velocities range from 7.6 to 8.6 km/s over most of the Mojave Desert. In the eastern Mojave Desert a true velocity near 7.8 km/s is inferred from reversing traveltime branches from Nevada Test Site explosions and the October 15, 1979, Imperial Valley earthquake (fig. 2a). Higher and lower apparent velocities can be interpreted to indicate structure on the Moho discontinuity, namely an asymmetric ridge, or hinge, trending north-northwest roughly from the Coxcomb Mountains to the east end of the Garlock fault (fig. 2c). This inferred ridge apparently dips more steeply to the west-southwest than to the east-northeast. It coincides with the east limit of earthquakes (see Fuis and Allen, 1979) and intermediate heat-flow values (see Lachenbruch, 1978) and a change from active strike-slip faulting to pre-Quaternary normal faulting. This boundary shall be referred to as the Mojave-Sonoran tectonic boundary. A semi-independent method of investigation also indicates a ridge or hinge on the Moho. Using blast reflections and assuming that the average crustal velocity is 6.2 km/s everywhere in the Mojave Desert, one can calculate Moho depths that when contoured indicate a deepening to the west-southwest from the Mojave-Sonoran boundary (fig. 2b). (If the average crustal velocity is 6.4 km/s, add about 2.5 km to the values shown, but the pattern remains

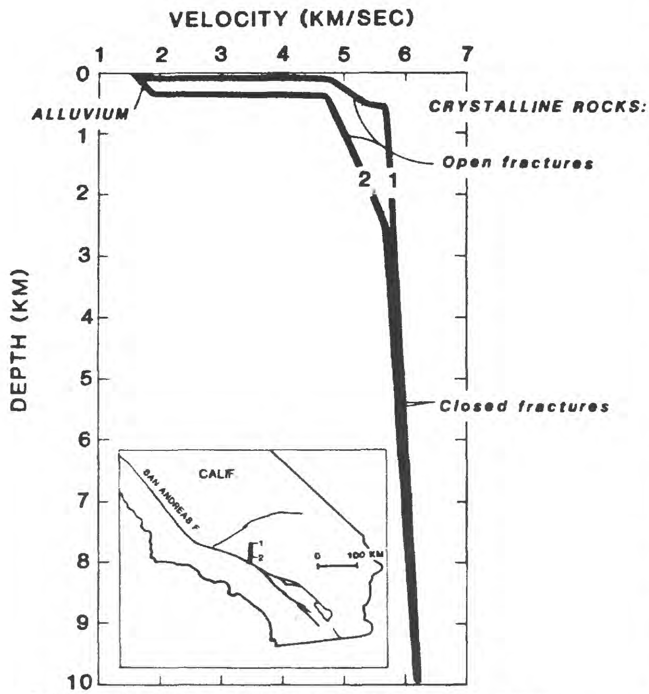

Figure 1. Preliminary velocity-depth curves from modeling seismic-refraction profile between Rogers Dry Lake and Holcomb Ridge, Mojave Desert, California. On index map, heavy line indicates profile; numbers indicate locations of curves.

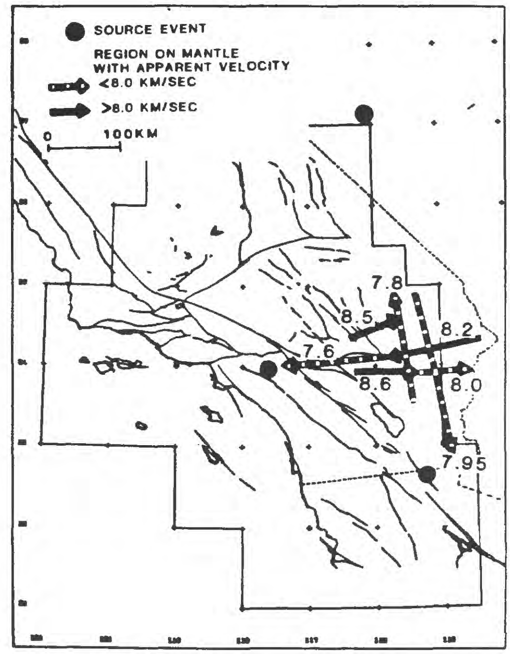

Figure 2a. Apparent velocities in eastern Mojave Desert, California, for mantle arrivals from 4 local source events. (One event is near Prescott, Arizona, off page).

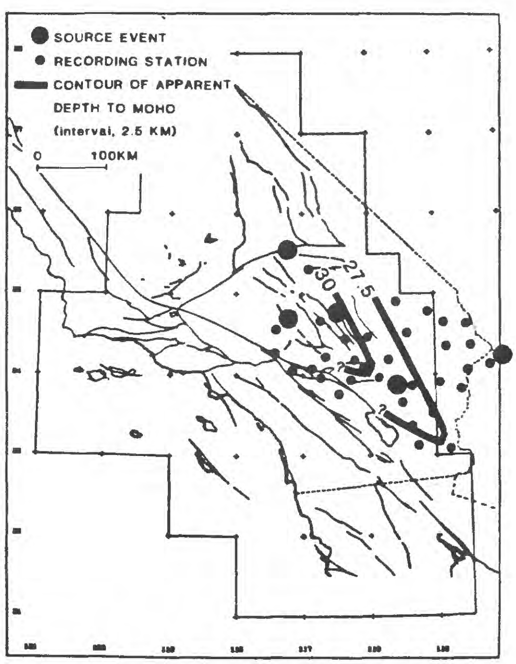

Figure 2b. Contour map of apparent depth to Moho in eastern Mojave Desert from blast reflections. Constant average crustal velocity of 6.2 km/s is assumed.

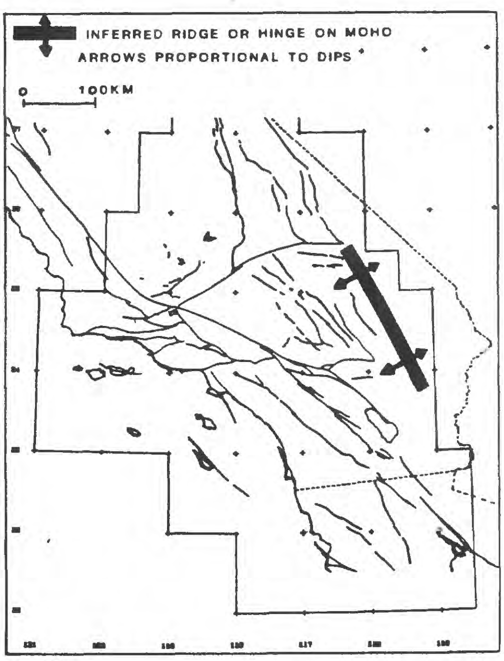

Figure 2c. Ridge or hinge on Moho inferred from figures 2a and 2b. This feature coincides with the Mojave-Sonoran tectonic boundary.

the same). Of course, if there is any gradient in the average crustal velocity--of which we are not aware--then this contour map does not simply reflect Moho depths.

5) A study of maps of residuals for mantle arrivals from local seismic events in southern California indicates a Moho depression of 3 to 8 km over its average depth (about 30 km) under the San Bernardino Mountains (Lamanuzzi, 1981).

6) The early teleseismic arrivals in the vicinity of the San Bernardino Mountains reported by Hadley and Kanamori (1977) must originate from relatively high velocities (deep?) within the mantle, because the thicker crust there would otherwise produce late arrivals.

References

Fuis, G. S., and Allen, C. R., 1979, The southern California cooperative seismic network: U.S. Geological Survey Earthquake Information Bulletin, v. 11, p. 196-204.

Hadley, D. M., and Kanamori, Hiroo, 1977, Seismic structure of the Transverse Ranges, California: Geological Society America Bulletin, v. 88, p. 1469-1478.

Lachenbruch, A. H., Sass, J. H., and Galanis, S. P., Jr., 1978, New heatflow results from southern California (abs.): EOS Transactions American Geophysical Union, v. 59, no. 12, p. 1051.

Lamanuzzi, V. D., 1981, Relative P_n travel-time residuals for stations in southern California: M.S. thesis, University of Southern California, Los Angeles, 117p.

Ponti, D. J., 1980, Stratigraphy and engineering characteristics of upper Quaternary sediments in the eastern Antelope Valley and vicinity, California: M.S. thesis, Stanford University, Stanford, 140p.

Roller, J. C., and Healy, J. H., 1963, Seismic-refraction measurements of crustal structure between Santa Monica Bay and Lake Mead: Journal of Geophysical Research, v. 68, no. 20, p. 5837-5849.

TECTONIC SIGNIFICANCE OF THE STRATIGRAPHY AND DISTRIBUTION OF CENOZOIC VOLCANIC ROCKS IN THE CENTRAL MOJAVE DESERT

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The nature and distribution of Cenozoic volcanic rocks in the Mojave Block yield clues to the tectonic history of this important part of Southern California. Volcanism commenced in the Mojave about 22 m.y. ago in a northwest-trending belt (herein named the "Mojave Volcanic Belt") that runs from the Lava Mtns.-Pilot Knob area in the northwest to Bristol Lake in the southeast. Volcanic rocks that erupted in this belt resemble those found in other parts of the western U.S., but the order of eruption is reversed -- andesites followed basalts instead of basalts following andesites. In the western U.S. the andesite-to-basalt transition is interpreted as the result of termination of subduction in the Tertiary. This transition is seen in parts of the Mojave, but the change back to andesite is unexplained.

Detailed mapping in the Sleeping Beauty Area of the Cady Mountains (Fig. 1) reveals the nature of these volcanic transitions. Stratigraphy of the area is summarized in Figure 2; based on analogy with surrounding areas, the section is probably early to middle Miocene. The oldest exposed formation is an eroded composite volcano comprising tephra, dikes, flows, and sills of hypersthene andesite. The lower andesite is overlain in buttress unconformity by a bimodal sequence of basalt and basaltic andesite flows interbedded with rhyodacite tuff. A series of high-K, low-Mg andesite flows rests unconformably on the bimodal sequence, and the section is capped by a welded rhyolite tuff and several hundred meters of sediments correlative with the Barstow Formation.

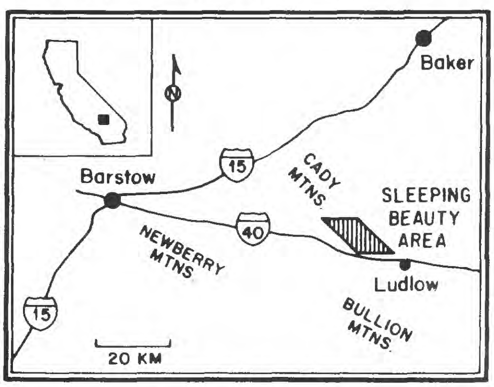

Figure 1. Location of the Sleeping Beauty Area

The lower andesite records a period of calc-alkaline, Cascade-type volcanism and is equivalent to subduction-related andesites found in other parts of the western U.S. The bimodal assemblage corresponds to post-subduction assemblages that develop in areas of extensional tectonics. The upper andesite is unexplained. Several other areas in the Mojave (e.g., Newberry Mtns., Bullion Mtns., and the area to the north of Barstow) show andesite-over-basalt sequences, but whether they can be correlated awaits further detailed mapping and dating. Whatever their origin, they demonstrate the presence of a widespread, post-basalt episode of intermediate volcanism in the Mojave Block.

Another clue to the tectonic history of the Mojave Block is the distribution of volcanic and sedimentary rocks. The Mojave Volcanic Belt developed in the early Miocene in a trough that cuts across current structural trends. The thickest piles of Tertiary volcanic and sedimentary rocks lie within this trough, and gold-silver mineralization, Quaternary volcanoes, and a chain of dry lakes all line up along its axis. Therefore, this trough has been a locus of volcanism, sedimentation, down-warping, and ore deposition since the early Miocene. It probably originally developed as a volcanic-tectonic trough analogous to those that sit above active subduction zones, with its sharp southwestern boundary serving as the volcanic "front." Its present-day expression as a chain of dry-lake basins and associated volcanoes may result from pull-apart tectonics related to the dominant strike-slip fault system.

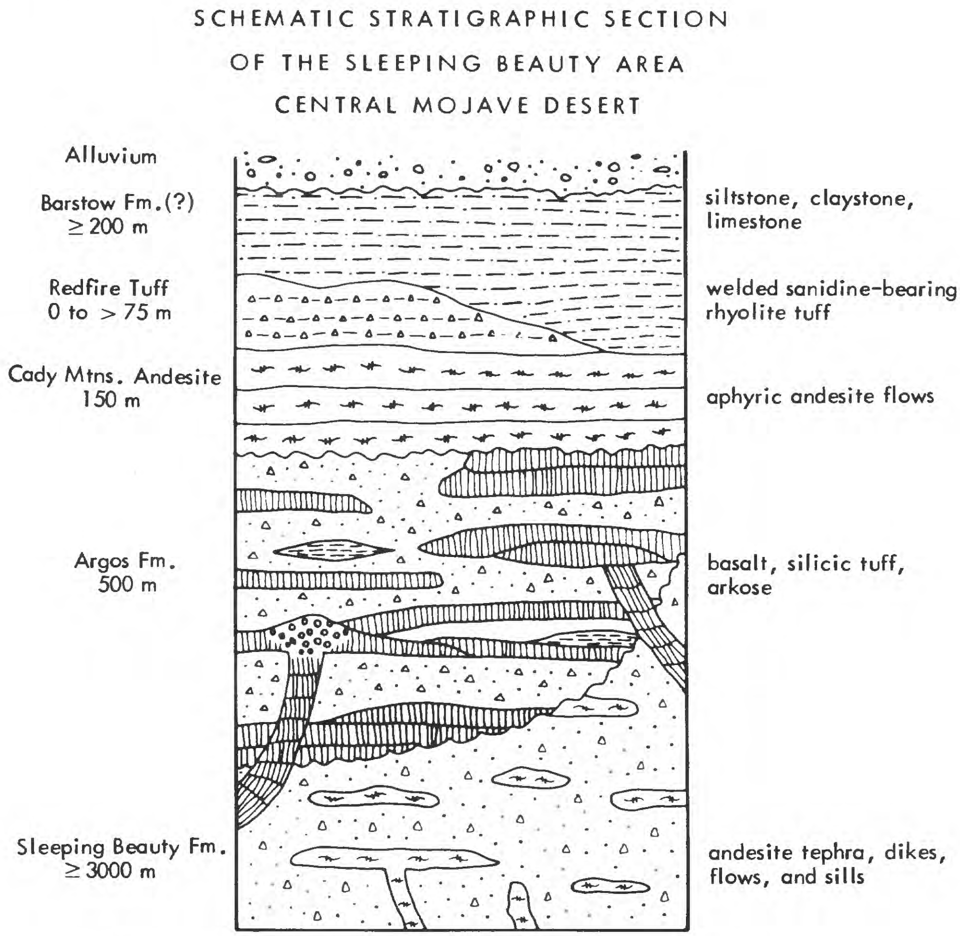

Figure 2. Stratigraphy of the Sleeping Beauty Area.
All formation names are currently informal.

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"CORE COMPLEXES" OF THE CORDILLERA

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The "metamorphic core complexes" widespread in the Cordillera are the tops of large lenses, by the separation of which Tertiary extension has been accommodated in the middle continental crust. These complexes consist of rocks that were at least 10 km deep before crustal extension; depth indicators include two-mica granites and the aluminum-silicate triple point in magmatic terrains, and kyanite greenschists in nonmagmatic ones. Ages of dominant metamorphism, and of magmatic rocks where present, range from Archean to Paleogene. The complexes commonly have cataclastic carapaces of Tertiary age, and are overlain tectonically by upper-crustal terrains. Tertiary listric normal faults merge with the upper surfaces of the lenses, and among the tracts typically rotated down on these faults are Tertiary basin strata, including landslide megabreccias from fault scarps, that now dip steeply or moderately into the gently-dipping faults that define the tops of the lenses. Seismic-reflection profiles in southern Arizona show that a thickness of the crust of about 12 km beneath the tops of the complexes consists of gently-tapered lenses, as wide as tens of km and as thick as 8 km, whereas the lower crust is subhorizontally layered. Apparently the lower crust is extended by smoothly ductile flow, the middle crust by the sliding apart of great lenses, and the upper crust by the collapse of listric normal-fault blocks. Similar complexes occur in extensional terrains around the world. Explanations invoking thrusting, magmatism, or sliding off domes are generally untenable.

LATEST CRETACEOUS AND EARLY TERTIARY THRUST FAULTING, REGIONAL METAMORPHISM, AND GRANITIC PLUTONISM, SOUTH-CENTRAL ARIZONA

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Within the region from the southern Santa Cruz River westward to Ajo and Organ Pipe Cactus National Monument, rocks in a number of mountain ranges are juxtaposed by thrust faults, regionally metamorphosed, and (or) intruded by garnet-two-mica granites. Field relations and K-Ar and U-Pb isotopic geochronology show that thrust faulting, metamorphism, and granitic plutonism were all related, as aspects of a single latest Cretaceous to early Tertiary orogenic episode.

The regionally metamorphosed rocks are chiefly metasedimentary quartzofeldspathic schist and phyllite, metarhyolite, metaconglomerate, epidotized sandstone, quartzite, and metagranite. They typically have moderately west dipping foliation, gently southwest plunging lineation, and gently west-northwest plunging late kink and crenulation folds. These metamorphic rocks were derived from Jurassic (Wright and others, 1981) and Cretaceous sedimentary, volcanic, and plutonic rocks. In several areas, for example the Baboquivari Mountains (Haxel and others, 1980) and Gunsight Hills, metamorphic rocks have been mapped into their unmetamorphosed protoliths.

In five ranges, these metamorphic rocks are overlain, along sharp, thrust-fault contacts, by Precambrian gneiss, Late Jurassic plutonic rocks, or Late Cretaceous granite. In each of these ranges, lineation in mylonitic rocks at the base of the upper plate is consistently parallel to that in the crystalloblastic rocks of the lower plate, indicating that thrusting was synmetamorphic. In three additional ranges, for example the Sheridan Mountains (Briskey and others, 1978), upward increase of textural grade within the metamorphic rocks, and analogy with the areas of exposed thrust faults, indicate the presence of buried thrust faults flanking these ranges. Each of these eight thrust faults has a lower plate consisting largely or entirely of Jurassic or Cretaceous supracrustal rocks. Seven of the eight thrust faults have single lower plates, but the thrust in the Quitobaquito Hills is underlain by a stack of some six imbricate thrust sheets (May and others, 1981). The regional spatial relationships of the eight thrust faults to one another are, in general, uncertain. However, in the southern Papago Indian Reservation (Haxel and others, 1980), geologic relations do indicate that Sierra Blanca and the hills east of Comobabi village are fensters in an extensive thrust sheet; hence, at least the Quijotoa-Brownell and Comobabi Mountains appear to be allochthonous.

In most areas, the regional metamorphic rocks are intruded by leucocratic, mesozonal to epizonal(?) early Tertiary granites characterized by various combinations of biotite, muscovite, and garnet.

Although these granites most commonly crosscut the fabric of the metamorphic rocks, locally the granites have crystalloblastic to mylonitic lineation parallel to the crystalloblastic lineation of the enclosing or nearby metamorphic rocks. In several of the granitic plutons, an older phase of the granite bears the regional metamorphic fabric, which is in turn crosscut by a homophanous younger phase of the granite. The garnet-two-mica granites are thus late synmetamorphic to postmetamorphic.

Thrust faulting and regional metamorphism postdate several Late Jurassic plutons, a Cretaceous conglomerate containing clasts of one such pluton, and a Late Cretaceous (L. T. Silver and T. H. Anderson, in Anderson and Roldan-Quintana, 1979, p. 80) granite. The youngest rocks affected by the orogenic episode are the garnet-two-mica granites. One of these granites, from the Coyote Mountains, has a U-Pb inferred isotopic age of approximately 58 m.y. (Wright and Haxel, 1982). K-Ar apparent isotopic ages of metasedimentary and metaplutonic rocks and of blastomylonites from one of the thrust zones range from 72 to 59 m.y. Regional metamorphism predates fissure veins as old as 45 and 52 m.y.; these veins are considered to have formed during postmetamorphic cooling and uplift (Tosdal, 1981). These and other geochronologic data indicate that orogenesis occurred during the interval from about 75 to 55 m.y. The available field and geochronologic data suggest that the overall sequence of events was thrust faulting, regional metamorphism, and granitic plutonism, with considerable overlap in most or all areas, and with local exceptions to this order in a few areas.

Late Cretaceous and (or) early Tertiary thrust faults that place crystalline Precambrian basement rocks or Mesozoic plutonic rocks atop metamorphosed Mesozoic supracrustal rocks occur not only in south-central Arizona, but also in west-central (Reynolds and others, 1980) and southwestern Arizona and adjacent California. This region of crystalline overthrusts lies between the region affected by the intracontinental Laramide orogeny of southeastern Arizona and adjacent areas (Drewes, 1978; Davis, 1979) and the "suspect," possibly accretionary, Mesozoic terranes of southern California (Coney and others, 1980). The orogenic episode described here has aspects in common with both the southeast-Arizona Laramide orogeny and Late Cretaceous-early Tertiary thrust faulting and metamorphism in southern California (Crowell, 1981).

References Cited

Anderson, T. H., and Roldan-Quintana, Jaimie, editors, 1979, Geology of northern Sonora, Guidebook-Field Trip #27, 1979 Annual Meeting of the Geological Society of America: Instituto de Geologia, U.N.A.M., Hermosillo, Sonora, Mexico, and the University of Pittsburgh, Pittsburgh, Pennsylvania, U.S.A.

Briskey, J. A., Haxel, Gordon, Peterson, J. A., and Theodore, T. G., 1979, Reconnaissance geologic map of the Gu Achi quadrangle, Pima County, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-965, scale 1:62,500.

Coney, P. J., Jones, D. L., and Monger, J. W. H., 1980, Cordilleran suspect terranes: Nature, v. 288, p. 329-333.

Crowell, J. C., 1981, An outline of the tectonic history of southeastern California, in Ernst, W. G., ed., The geotectonic development of California (W. W. Rubey Volume No. 1), p. 583-600.

Davis, G. H., 1979, Laramide folding and faulting and southeastern Arizona: American Journal of Science, v. 279, p. 543-569.

Drewes, Harald, 1978, The Cordilleran orogenic belt between Nevada and Chihuahua: Geological Society of America Bulletin, v. 89, p. 641-657.

Haxel, Gordon, Wright, J. E., May, D. J., and Tosdal, R. M., 1980, Reconnaissance geology of the Mesozoic and lower Cenozoic rocks of the southern Papago Indian Reservation, Arizona: A preliminary report: Arizona Geological Society Digest, v. 12, p. 17-29.

Haxel, Gordon, May, D. J., Wright, J. E., and Tosdal, R. M., 1980, Reconnaissance geologic map of the Baboquivari Peak quadrangle, Arizona: U.S. Geological Miscellaneous Field Studies Map MF-1251, scale 1:62,500.

May, D. J., Tosdal, R. M., and Haxel, Gordon, 1981, Imbricate thrust faulting of Late Cretaceous or early Tertiary age, Organ Pipe Cactus National Monument, southwestern Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 13, in press.

Reynolds, S. J., Keith, S. B., and Coney, P. J., 1980, Stacked overthrusts of Precambrian crystalline basement and inverted Paleozoic sections emplaced over Mesozoic strata, west-central Arizona: Arizona Geological Society Digest, v. 12, p. 45-51.

Tosdal, R. M., 1981, Late Cretaceous to late Tertiary base- and precious-metal mineralization, south-central Arizona: this volume.

Wright, J. E., Haxel, Gordon, and May, D. J., 1981, Early Jurassic uranium-lead isotopic ages for Mesozoic supracrustal sequences, Papago Indian Reservation, southern Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 13, in press.

Wright, J. E., and Haxel, Gordon, 1982, A garnet-two-mica granite, Coyote Mountains, southern Arizona: Geologic setting, uranium-lead isotopic systematics of zircons, and nature of the granite source region: Geological Society of America Bulletin, in press.

A KINEMATIC FRAMEWORK FOR CONTEMPORARY BLOCK TECTONICS

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The gross pattern of Quaternary faulting throughout California and Nevada together with well-determined earthquake fault-plane solutions show a systematic relation between the orientations of fault planes and slip directions. Kinematically, this relation is consistent with deformation accompanied by the jostling of crustal blocks in a regional stress field dominated by the Pacific-North American plate interaction, in which the trajectories of the greatest horizontal compressive stress, S_{Hmax}, and the least horizontal compressive stress, S_{Hmin}, generally trend north-northeast and west-northwest, respectively. The essence of this kinematic pattern is illustrated in Figure 1 in terms of the response of a cluster of blocks to an increment of north-south shortening and east-west extension with the individual block boundaries (active faults) defined by conjugate right- and left-slip faults that strike to the northwest and northeast, respectively, and either north-striking normal faults or east-striking thrust faults.

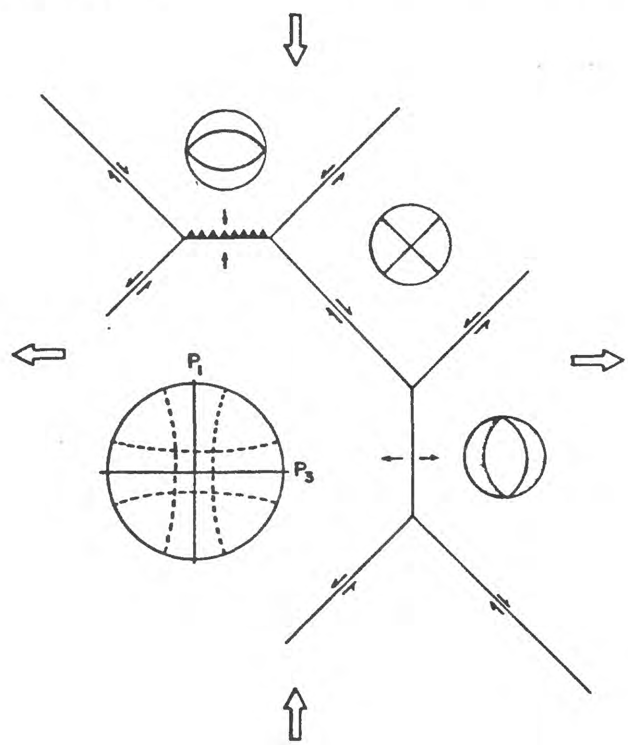

Figure 1. Map view of idealized block geometry and relative displacements (small arrows) due to an overall increment of north-south shortening and east-west extension (large arrows) with typical focal mechanisms (balloons with compressional quadrants darkened) for earthquakes on block boundaries. Stereo plot in lower left corner shows orientation of vertical P_1 and P_3 planes that contain focal mechanisms P and T axes, respectively; dashed lines indicate $\pm 20^\circ$ deviation from these planes. Horizontal traces of P_1 and P_3 correspond to S_{Hmax} and SHmin, respectively.

The blocks are presumably at least as thick as the seismogenic crust (10 to 20 km in most of California and Nevada) with the lower surface corresponding to a decoupling zone or zones somewhere in the middle to lower crust or perhaps the uppermost mantle. Implicit in this concept of blocklike behavior is the assumption that the continental crust is distinctly heterogeneous in strength with active faults (block boundaries) representing pre-existing planes of weakness.

A set of wooden blocks provides a simple physical means for demonstrating the response of three basic configurations of such blocks to an increment of north-south shortening. The response of a cluster of blocks to the spreading configuration (Fig. 2) is characterized by opening along north-striking planes and strike-slip along conjugate northeast- and northwest-striking planes. The thrusting configuration is

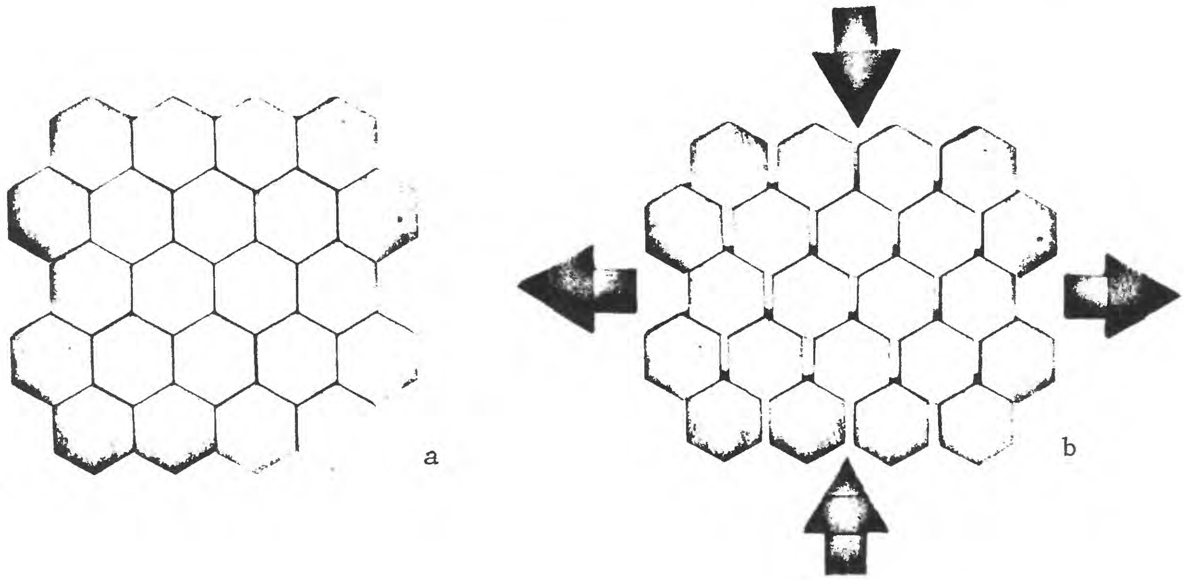

Figure 2. (a) Cluster of wooden blocks in the spreading configuration and (b) response to north-south shortening.

formed by rotating the cluster of blocks 90° (and beveling the east-striking edges of the block). In this case, an increment of north-south shortening results in reverse slip along the east-striking planes accommodated slip along conjugate strike-slip faults. Finally, the strike slip configuration results from introducing several split blocks into the cluster to form a single, through-going fault that strikes either to the northwest or northeast. Overall deformation of both the spreading and thrusting configurations is irrotational while the strike-slip configuration involves a rotational component of deformation, clockwise for right slip and counterclockwise for left slip. Common to each configuration is an increment of east-west extension accompanying the imposed increment of north-south shortening.

By way of kinematic analogs, the spreading configuration corresponds to deformation in the Basin and Range province, the thrusting configuration to deformation in the Transverse Ranges, and the strike-slip configuration to deformation along the San Andreas fault system as well as deformation internal to the Mojave block. The upper half of the diagram in Figure 1 is an analog for the contemporary interaction among the San Andreas, Garlock, and Big Pine faults, and the Y-shaped pattern in central part of Figure 1 is an analog for the late Miocene interaction between the conjugate Las Vegas and Lake Meade strike-slip faults described by Bohannon (this volume). Implications for contemporary tectonics include westward displacement of the Sierra Nevada block with respect to the Mojave block and the interior of the North American plate, oblique thrusting of the Salinian and western Transverse Range blocks over the Pacific plate, and a progressive increase with time of the big bend in the San Andreas fault. Details are presented in a manuscript entitled "Contemporary Block Tectonics: California and Nevada" that has been submitted to the Journal of Geophysical Research for publication.

Reconnaissance Study of Mesozoic Plutonic Rocks in the Mojave Desert Region

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The purpose of this paper is twofold; first to give a brief overview of Mesozoic plutonism in the Mojave Desert region, and second to describe a well exposed Cretaceous batholith in the central Mojave Desert.

Plutonic rocks in the Mojave Desert region are highly variable in composition, in that they exhibit both alkaline and calc-alkaline affinities. Despite this range in composition, reconnaissance studies indicate that temporally related intrusive rocks can be classified on the basis of lithology. Isotopic age data reported by Armstrong and Suppe (1973), Miller (1976), Calzia and Morton (1980), Cox and Morton (1980 and unpublished data), Miller and Morton (1980), and Miller and others (1980) provide age control for several lithologic types. Correlations are made on the basis of reconnaissance lithologic comparisons with these isotopically dated rocks, and are subject to revision as more mapping, geochemical, and isotopic age data become available.

Permian and Triassic Plutonic Rocks

The earliest dated batholithic arc in southern California is characterized by at least two distinct suites of late Permian and early Triassic intrusive rocks. These rocks are exposed in a poorly defined northwest-trending belt along the western margin of the Mojave Desert, primarily in the Chocolate Mountains, the Granite Mountains near Victorville, the El Paso Mountains north of the Garlock Fault, and west of the San Andreas Fault in the San Gabriel Mountains (Fig. 1). Other bodies, tentatively assigned an early Triassic age, are exposed in the Little Chuckwalla and San Bernardino Mountains. The first suite is characterized by quartz-poor, garnet-bearing monzonites with abundant potassium feldspar, and by the presence of clinopyroxene and hornblende. This suite has K-Ar cooling ages between 230 and 235 m.y. and occurs in the Granite Mountains-Victorville area and in the San Bernardino Mountains. The second suite, similar to the Mt. Lowe granodiorite in the San Gabriel Mountains, is exposed in the Chocolate and Little Chuckwalla Mountains. This calc-alkaline suite is characterized by foliated, hornblende-biotite, garnet-bearing monzodiorite to granodiorite, with an apparent age of 220 m.y. Permo-Triassic hornblende-rich quartz monzodiorite to tonalite in the El Paso Mountains has a ^{40}Ar-^{39}Ar age of 252 m.y. Because of the radiometric age, there is some doubt whether this rock unit can be correlated with either of the two suites described.

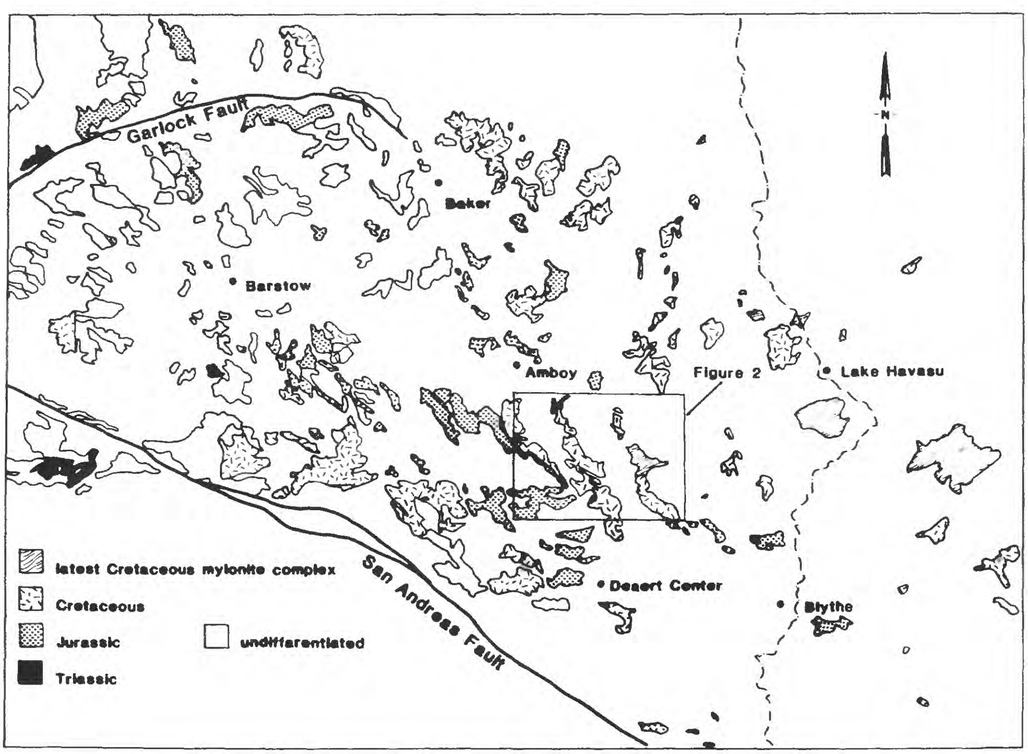

Figure 1. Distribution of Mesozoic plutonic rocks in the Mojave Desert region

Jurassic Intrusive Rocks

Intrusive rocks of Jurassic age have been identified in a northwest-trending belt that extends from Sonora, Mexico, through western Arizona, west of the Colorado River in the Big Maria Mountains, and northwestward beyond Baker. These temporally related rocks can be characterized as two suites in the central Mojave Desert, divisible geographically at the Bristol Mountains, north of Amboy. The Jurassic terrane north and east of the Bristol Mountains is characterized by a suite of medium- to coarse-grained, hornblende-biotite monzonite and syenite, with K-Ar cooling ages between 145 and 158 m.y. Jurassic intrusive rocks south of the Bristol Mountains are chiefly hornblende-biotite monzogranite and granodiorite, with pale violet potassium feldspar phenocrysts and clotted mafic minerals. K-Ar age determinations suggest a cooling age of approximately 165 m.y. Batholithic rocks in the northern Bristol, Bullion and Pinto Mountains appear to intrude hypabyssal and volcanic equivalents. This intrusion resulted in hydrothermal alteration of the volcanic rocks and weak Au-Ag-Cu mineralization.

Cretaceous Plutonic Rocks

Cretaceous plutonism was concentrated in the central Mojave Desert, producing large composite batholiths. Northeast of this area plutonism is characterized by discrete intrusive bodies. Hornblende-bearing biotite granodiorite and granite characterize the older (approximately 90 m.y.) Cretaceous suite exposed in the Old Woman, Turtle, and Riverside Mountains. A younger, more voluminous suite with K-Ar (biotite) ages between 82 and 54 m.y. is typically more quartz-rich. It ranges from hornblende-biotite granodiorite and granite to two-mica, garnet-bearing granite. The Cadiz Valley batholith, an example of this latter suite, is currently being mapped by members of the U.S. Geological Survey, and will be outlined in the following section.

Cadiz Valley Batholith

The late Cretaceous Cadiz Valley batholith is an elongate, northwest-trending plutonic body located in the east central Mojave region that underlies more than 1700 km^2 (Fig. 2). The batholith intrudes Jurassic plutonic rocks on the north, west and south, and is bounded on the east by Precambrian rocks of the Turtle Mountains. Screens of metasedimentary and metaigneous rocks strike northwest, and have steep to vertical dips.

At least three separate intrusive phases make up the Cadiz Valley batholith. The oldest is a biotite-sphene granodiorite. It is spatially associated with prebatholithic rocks, both at the

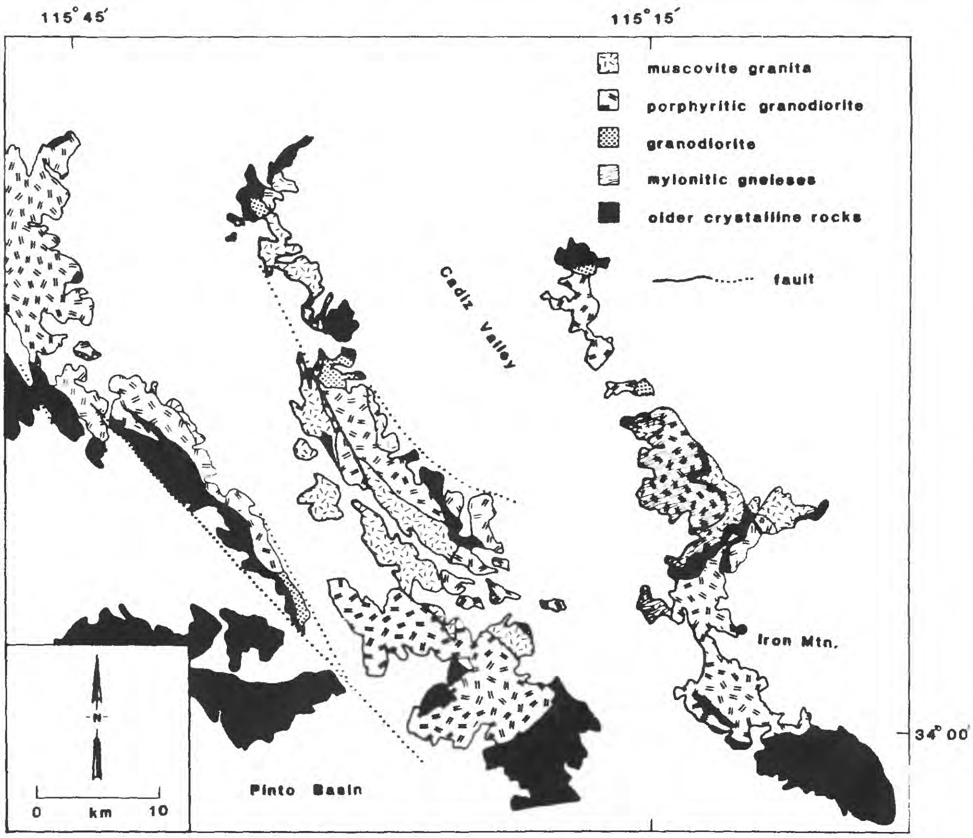

Figure 2. Generalized geologic map of the Cretaceous Cadiz Valley batholith. Cenozoic deposits unpatterened.

margin and in the interior of the batholith where screens of older rocks occur. The granodiorite is commonly strongly foliated and is host to a wide range of wallrock inclusions and mafic xenoliths. Where xenoliths are absent, the granodiorite contains 23-25% modal quartz, 60-75% modal plagioclase, and as much as 20% modal potassium feldspar as equant grains as large as 1 cm. Mafic minerals include biotite and rare hornblende, with accessory sphene, allanite, magnetite, apatite, and zircon.

A relatively quartz-rich (25 to 40% modal quartz), variably porphyritic granodiorite to monzogranite intrudes the granodiorite phase. The coarsely porphyritic rocks of this phase are characterized by perthitic microcline megacrysts in a groundmass of medium-grained, equigranular plagioclase, quartz, orthoclase or perthite, and biotite, commonly with muscovite and accessory apatite, sphene, zircon, and allanite. Most of the megacrysts are elongate (as much as 15 cm in greatest dimension), with well-formed but rough crystal faces, and concentric zones of included minerals. Irregular clots of potassium feldspar may constitute 85% of the volume and are dispersed within both porphyritic and matrix-rich phases. Schlieren and wallrock inclusions, common in the quartz-poor granodiorite, are rare except as huge screens within the porphyritic granodiorite.

Leucocratic, subequigranular, muscovite-bearing, biotite monzogranite occurs as irregular bodies concentrated in the central part of the batholith. This phase shows gradational contact relations with the porphyritic granodiorite, but the monzogranite is faulted against the quartz-poor granodiorite. Limited field evidence and petrologic relations suggest that the structureless, two-mica monzogranite is the latest phase. Intrusive relations in the Iron Mountains, however, indicate that a deformed, equigranular, two-mica monzogranite is older than some of the porphyritic granodiorite.Accessory muscovite (1 to 5% total volume) in the monzogranite appears to be both primary and secondary in origin. Coarse subhedral flakes as much as 5 mm in diameter are dispersed irregularly in the rock. Secondary sericite is commonly developed within the cores of plagioclase, and along an extensive northwest-trending joint system it is developed in association with hematite after pyrite.

Fine- to medium-grained, garnet-muscovite aplite and pegmatite dikes are common along the margin of the batholith in the granodiorite and the porphyritic granodiorite. Garnet-bearing aplite dikes in the central Coxcomb Mountains have a well-developed northeast-trending mylonitic lineation.

The limited isotopic age data, together with an estimated cooling rate, suggest that the Cadiz Valley batholith was emplaced between 75 and 85 m.y. into a terrane of Precambrian crystalline, Paleozoic metasedimentary, and high level Jurassic intrusive rocks. Early intrusion was characterized by xenolith-rich, quartz-poor granodiorite. Later leucocratic granodiorite and two-mica monzogranite have K-Ar (muscovite) cooling ages between 69 and 65 m.y. These phases were subsequently intruded by late-stage, two-mica, garnet-bearing aplite and pegmatite dikes, some of which bear a mylonitic lineation. In the Iron Mountains on the east side of the batholith, undeformed, porphyritic granodiorite is increasingly deformed toward the top of the intrusion, and ultimately grades into mylonitic gneisses. Along the northern and western boundaries of the batholith, however, granodiorite and porphyritic granodiorite cleanly intrude the Jurassic wallrocks, without being strongly deformed. The mode of intrusion and emplacement of the Cadiz Valley batholith, an example of late Cretaceous plutonism, is yet unresolved, and worthy of further study.

REFERENCES

Armstrong, R. L., and Suppe, J., 1973, Potassium-Argon geochronometry of Mesozoic igneous rocks in Nevada, Utah and southern California: Geol. Society America Bull., v. 84, p. 1375-1392.

Calzia, J. P., and Morton, J. L., 1980, Preliminary compilation of isotopic age dates within the Needles $1^{\circ} \times 2^{\circ}$ quadrangle, California and Arizona: U. S. Geological Survey, Open-File Report 80-1301.

Cox, B. F., and Morton, J. L., 1980, Late Permian plutonism, El Paso Mountains, California: Geol. Society America Abstr. Programs, v. 12, p. 103.

Miller, C. F., 1976, Alkali-rich monzonites, southern and central California--a unique magmatic episode?: Geol. Society America Abstr. Programs, v. 8, p. 395-396.

Miller, C. F., Sparkes, A. K., Stoddard, E. F., Hoisch, R. D., and Hurst, R. W., 1980, Old Woman-Piute Range plutonic complex, southeastern California: Geol. Society America Abstr. Programs, v. 12, p. 141.

Miller, F. K., and Morton, D. M., 1980, Potassium-Argon geochronology of the eastern Transverse Ranges and southern Mojave Desert, southern California: U. S. Geological Survey Prof. Paper 1152, 30 p.

REGIONAL GRAVITY STUDIES, NORTHERN SONORA, MEXICO

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Bouguer gravity data provide information about regional structure of an area in northern Sonora located about 100 km east of the Gulf of California. The map shows that the gravity decreases from west to east, rapidly at first along a steep gradient zone, flattens to form a broad terrace in the central area, then steepens again with the lowest values over the Sierra Madre Occidental (fig. 1). The broad gravity terrace is of particular interest and extends south from Arizona to Moctezuma where a steep gradient zone marks the southern boundary. The effect of topographic changes on the gravity field has been examined by Woollard, Machesky, and Monges-Caldera (1969). They concluded that many broad negative anomalies in northern Sonora were not elevation dependent.

The gravity terrace appears as a broad low on the profile and may represent a block of low-density crust west of the Sierra Madre Occidental. Limited granitic rocks outcrop and it is proposed that there may be a major granitic batholith beneath the predominantly Tertiary volcanic and recent alluvial cover rocks. The granitic rocks may have been a former mountain root system, which were the source area for thick Cretaceous sedimentary rocks that are widespread in the region. Anderson and Silver (1979) from regional isotopic studies have proposed a megashear extending from the Inyo Mountains, Calif., across the Mojave desert, and into northern Sonora with an east-southeasterly projection which would coincide with the high gravity gradient zone just north of Hermosillo. The prominent gravity gradient zone may reflect a transition between oceanic crust in the vicinity of the Gulf of California spreading center and continental crust in the vicinity of the proposed granitic block (gravity terrace).

REFERENCES

Anderson, T. and Silver, L. T., 1979, The role of the Mojave-Sonora megashear in the tectonic evaluation of northern Sonora, in Geology of northern Sonora, guidebook - field trip no. 27, editors Thomas H. Anderson and Jaimie Boldan - Quintana: Instituto de Geology, U.N.A.M., Hermosillo, Sonora, Mexico and the University of Pittsburgh, Pittsburgh, PA, U.S.A.

U.S. Geological Survey, 1977, Preliminary simple Bouguer gravity map of north-eastern Sonora, northwestern Chihuahua, and southeastern Arizona: U.S. Geological Survey Open-file Map 77-473.

Woollard, G. P., Machesky, L., and Monges-Caldera, J., 1969, A regional gravity survey of northern Mexico and the relation of Bouguer anomalies to regional geology and elevation in Mexico: Part 1 of final report, contract D.A.C.A. 71-67-C-0010, University of Hawaii and the U.S. Army Topographic Command, University of Hawaii, Honolulu, Hawaii, 43 p.

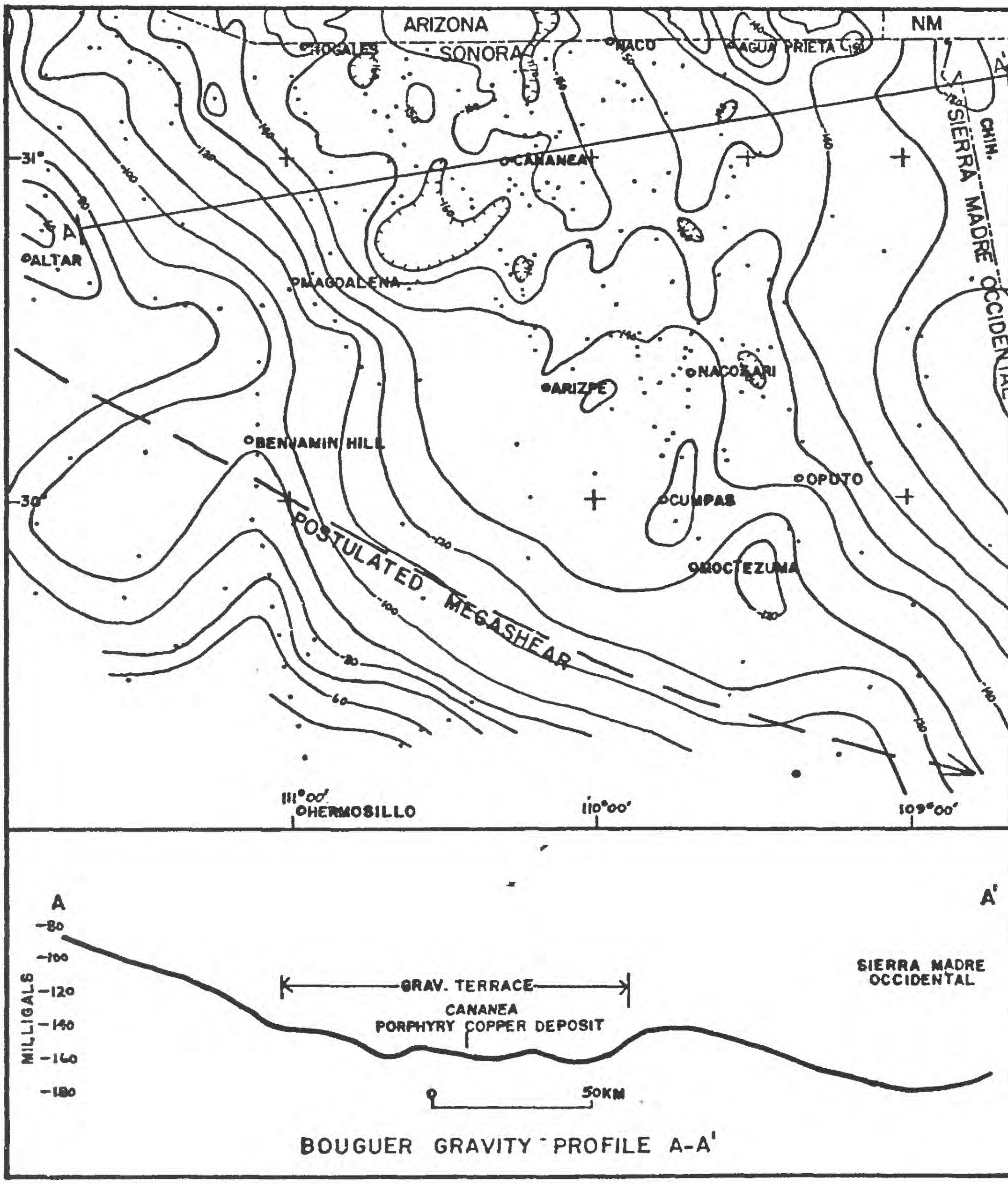

Figure 1. Bouguer gravity map (modified from U.S. Geological Survey, 1977) and Bouguer gravity profile. Gravity stations shown by solid dots. Contour interval 10 milligals. Megashear postulated from regional isotopic studies by Anderson and Silver (1979).

OBSERVATIONS AND SPECULATIONS REGARDING THE RELATIONS AND ORIGINS OF MYLONITIC GNEISS AND ASSOCIATED DETACHMENT FAULTS NEAR THE COLORADO PLATEAU BOUNDARY IN WESTERN ARIZONA

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One of the most obdurate problems confronting students of the mylonitic-gneiss complexes and associated detached upper plates that are unmetamorphosed but highly distended, has been the spatial and temporal relation between mylonitization, detachment faulting, and extension. A common view is that the mylonization is late Cretaceous to Oligocene, although a few isotopic ages are as young as Miocene, whereas the detachment faulting is middle to late Miocene. This hypothesis is based on the abrupt break in metamorphic grade at the detachment faults, the absence of mylonization in the upper plate, the common early Tertiary isotopic ages on the mylonite gneiss, and the truncation of mylonite structures by the detachment faults. An inescapable corollary of this hypothesis is that the upper plates are gravity-glide masses, and that these masses slid along surfaces--the detachment faults--exactly coincident with some older but poorly understood surfaces truncating the mylonite gneisses.

Thus Shackleford (1980) in his excellent treatment of Tertiary denudation faulting in the Rawhide Mountains of Arizona, concluded that (1) The autochthonous mylonitic gneisses reflect a tectonic event separate and older than that represented by the Rawhide (detachment) Fault (RF), and (2) Denudation occurred through northeast-directed gravity gliding of upper plate allochthonous rocks. Our observations and speculations are based on several years of detailed mapping of upper plate rocks in an area directly north of that mapped by Shackleford and extending toward the Colorado Plateau.

As mapped by Shackleford and by us, the RF dips gently to the north and northeast in the direction of the Colorado Plateau, which is as close as 40 km. If the upper plate is an allochthon that has moved northeast, how does the plate--and the associated RF--terminate in that direction? Assuming the Colorado Plateau is not allochthonous, the RF must end by shoaling, by offset along a transcurrent fault, or by decrease in displacement northeastward. We have searched for possible terminations of the upper plate, and have found none. The RF does not shoal upward. The Artillery fault, a possible condidate for a shoaling RF, is not a continuation of the RF, but is similar to other faults cutting upper plate rocks. Upper plate Tertiary rocks extend, in depositional contact, onto basement rocks of Colorado Plateau type northeast of the Aubrey Lineament, which separates terranes that differ greatly in morphology, structure, and types of rocks present (Lucchitta and Suneson, 1979). The Sandtrap Wash fault, which Shackleford suggested might terminate the upper plate, is part of the lineament. Our mapping shows that displacement along this fault decreases rapidly northward, where the fault merges with a north-trending normal fault that bounds the McCracken Mountains on the east. We have found no evidence of strike-slip displacement.

These relations indicate that the upper plate cannot have moved northeastward by gravity gliding. Possible alternatives are few. We suggest the following model:

The area mapped by us is near the northeast edge of a terrane marked by metamorphic-core complexes, extreme distension, and associated detachment faulting. Both metamorphism and faulting die out to the northeast, and the RF terminates in that direction by decrease in displacement, feathering into many breaks, and changing into a zone of distributive shear.

The upper plate is anchored at its northeast end to autochthonous basement rocks of Colorado Plateau type. To the southwest, in the vicinity of the Rawhide Mountains, it has been stretched and attenuated by listric faulting, but, fundamentally, it is in place. Thus, it is autochthonous or nearly so. The lower, gneissic, plate has moved southwestward, toward a culmination of the metamorphic-complex terrane, by non-brittle underflow. Hence, it is allochthonous. In such a tectonic regimen ("conveyor-belt tectonism" in our parlance), the upper plate merely goes along for the ride, being stretched and pulled apart in the process. Near the margins of the area affected by the process, this stretching is manifested mostly by brittle fracture (listric faults). In more central areas, where rock temperatures probably are more elevated, attenuation may occur by more ductile processes, as in the Big Maria Mountains (Hamilton, 1964).

The basal detachment fault (RF) is a locus of stress concentration that is difficult to visualize as following pre-existing structures, because it cuts the grain of such structures. We suspect that it is the locus of a change from brittle to non-brittle deformation, as suggested by Armstrong and Dick (1974), associated at the time of deformation with a steep temperature gradient.

Although the model can accomodate the interpretation that the formation of the mylonite gneiss was an early Tertiary event distinct from the late Tertiary detachment faulting, this interpretation does not explain the common and close spatial relation between basal detachment faults and mylonite gneiss, or the close coincidence in space of two kinematic events widely separated in time.

Another interpretation is that formation of the mylonite gneisses, movement on the RF, volcanism, deposition of Tertiary rocks, and listric faulting in the upper plate all are products of the same tectonic disturbance and are nearly of the same age. This interpretation requires that the early Tertiary K-Ar ages on the gneiss result from incomplete expulsion of argon during metamorphism of a Precambrian protolith, and thus are to be viewed as maximum ages.

We suggest that the area mapped by Shackleford and by us and containing the RF and associated upper plate is at the northeastern margin of the tectonic disturbance. To the southwest, heating, metamorphism, structural disturbance, and uplift were much greater. Little beside lower plate gneiss is present in that area today, but an indication of what once was present can be obtained from studying tectonic sheets that became interleaved with accumulating sediments of the upper plate. These sheets are gravity-glide blocks that came from the southwest. In places, they are stacked on top of each other, and collectively they form an inverted sequence consisting of greenschist-facies metasedimentary and metavolcanic rocks at the base, then quartzite and marble, and finally sheared and biotite-rich granitic rocks at the top. They represent the carapace at the top of the gneiss complexes, removed by progressive unroofing of the complexes as they were being uplifted. The sheets formed in response to uplift. The RF, in contrast, was formed by non-brittle underflow that contributed to the uplift.

In summary, we suggest that the lower plate mylonite gneiss and the RF are two expressions of an intense Tertiary (Miocene) thermal and deformational event that included volcanism, extension, listric and detachment faulting, basin formation, and the emplacement of imbricate gravity-glide masses that slid northeastward from an uplifted metamorphic-complex terrane. This disturbance was restricted to the area southwest of the Colorado Plateau, so that the degree of metamorphism, mylonitization, and displacement on the RF decrease northeast from the Rawhide Mountains. The origin of the RF is not related to gravity gliding, as Shackleford (1980) suggested, but probably to non-brittle underflow. However, both underflow and the gravity-glide emplacement of tectonic sheets within the upper plate are related to intumescence and distension of the area of the metamorphic-core complexes.

The possibility cannot be excluded that, for reasons not yet understood, many of the areas marked by mylonitic gneiss and distended upper plates were the locus of abnormal heating, mobilization and extention more than once in geologic time.

REFERENCES

Armstrong, R. L., and Dick, H. J. B., 1974, A model for the development of thin overthrust sheets of crystalline rock: Geology, v. 2, no. 1, p. 35-40.

Hamilton, W. B., 1964, Geologic map of the Big Maria Mountains NE quadrangle, Riverside County, California, and Yuma County, Arizona: U. S. Geological Survey Geologic Quadrangle Map GQ-350.

Lucchitta and Suneson, 1979, Origin of a northwest-trending lineament, west-central Arizona (abs.): Geological Society of America Abstracts with Programs, v. 11, no. 3, p. 89.

Shackleford, T. J., 1980, Tertiary tectonic denudation of Mesozoic-early Tertiary(?) gneiss complex, Rawhide Mountains, western Arizona: Geology, v. 8, no. 4, p. 190-194.

HEAT FLOW AND ITS IMPLICATIONS FOR TECTONICS AND VOLCANISM IN THE BASIN AND RANGE PROVINCE

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The portion of the Basin and Range Province to the west of the Colorado Plateau (the Great Basin, Figure 1) has high and variable heat flow (~2.1 HFU ± 40%) and there is a very rapid transition to low heat flow (about 1 HFU) at its western boundary with the Sierra Nevada (Roy and others, 1972; Lachenbruch and Sass, 1977; Henyey and Lee, 1976). Preliminary analysis of recent data in the part of the Basin and Range Province to the south of the Colorado Plateau (the Sonoran Desert, Figure 1) shows that it has similarly high and variable heat flow which undergoes a rapid transition to moderate heat flow (about 1.6 HFU) at its western boundary with the Mojave block, MB, Figure 1 (Lachenbruch and others, 1978). This boundary, which coincides with the projection of the Death Valley fault zone and with the eastern limit of active seismicity (Fuis and Allen, 1979) probably separates a region of San Andreas-type strike-slip tectonics to the west from the region of Basin-and-Range type extensional tectonics to the east. At the eastern boundary of the Great Basin and the northern boundary of the Sonoran Desert (Figure 1), the high heat flow undergoes a gradual transition (modified to some extent by lateral and vertical regional water flow) to moderate heat flow in the relatively stable interior of the Colorado Plateau (Bodell and Chapman, 1980; Reiter and Shearer, 1979). Hence in this part of the continent, the region of high and variable heat flow is coextensive with a region of late Cenozoic tectonic extension, as such deformation is characteristic of the Basin and Range Province.

High and variable heat flow is an expectable consequence of prolonged tectonic extension provided that (as in the Basin and Range Province) such extension does not result in rapid subsidence and massive sedimentation (see e.g., McKenzie, 1978). To maintain isostatic balance and conserve mass, it is necessary that warmer material move upward from depth to replace material that moves laterally in the extending layer. Heat carried convectively by this upward motion could account for the elevated regional heat flow observed. The associated elevated thermal gradients and relatively open fractures in an extending brittle layer could facilitate hydrothermal convection which probably accounts for much of the local variability of heat flow in the Basin and Range Province (Lachenbruch and Sass, 1977).

The size of the regional heat-flow anomaly caused by tectonic extension depends upon how rapidly extension is (and has been) taking place, and upon the nature of the compensating upflow of mass in the lithosphere, i.e., whether upflow is entirely in the solid state as a result of lithosphere thinning caused by normal or listric faulting and ductile stretching, or whether at some depths the upflowing materials are magmas, accommodating extension and thinning by the formation of dikes and sills. Simple mathematical models of these processes indicate that the heat flow observed in the Basin and Range Province can be accounted for with no anomalous conductive contribution from the asthenosphere if average extension rates were in the range 1/2 to 1 1/2 %/m.y. for the past 15 or 20 m.y. (Lachenbruch and Sass, 1978; Lachenbruch, 1978; Lachenbruch and others, 1976). Such rates are consistent with estimates by Stewart (1978) for extension of the Great Basin. However, the similarity of heat flows in the Great Basin and the Sonoran Desert, and the evidence that their extensional histories during the past ~5 m.y. have been different requires further investigation. Extreme models such as those requiring extension by a factor of two (Hamilton, 1980) are not precluded (e.g., 2 1/2 %/m.y. for 28 m.y. yields a strain of $\exp[0.025 \text{ m.y.}^{-1} \times 28 \text{ m.y.}] = 2$). For such extreme models, the details of the kinematics of upflow, and the extensional history are more severely constrained by the heat-flow observations. For higher heat-flow subprovinces like the Battle Mountain high in northern Nevada and the Rio Grande Rift in New Mexico, prolonged extension at average rates ~3%/m.y. are consistent with a wide variety of models (Lachenbruch and Sass, 1978). In general, the fact that present heat flow is sensitive to the history of late Cenozoic extension makes it a useful test for models of extensional history derived from other sources of information.

The foregoing considerations are based on the balance of mass (mass must rise to compensate for that moving laterally) and of heat (the increase of lithosphere temperature and heat flow must correspond to the heat carried by the rising mass). Similar considerations might be applied in a cruder way to obtain estimates of extension rates at active volcanic centers in regions of tectonic extension. In contrast to the Great Basin and Sonoran Desert with dimensions of many hundreds of kilometers and heat-flow anomalies on the order of 1 HFU persisting perhaps for 10 m.y. or more, volcanic centers within these regions have had dimensions on the order of 10 km with anomalous heat loss on the order of 10 HFU (e.g., Lachenbruch and others, 1976; see also Morgan and others, 1977) and they probably persisted only for periods on the order of a few million years.

The heat lost from such volcanic centers (principally by hydrothermal discharge) is believed to be supplied from upper crustal silicic magma chambers (e.g., Smith and Shaw, 1975; Christiansen, 1978). However, such chambers must be repeatedly resupplied with heat from depth for otherwise they would crystallize many times over during the volcanic episode (e.g., Lachenbruch and others, 1976). The most obvious source of this heat is basalt drawn from the asthenosphere (Smith and Shaw, 1975). To supply the heat loss at the observed rate (say 15 HFU) it would be necessary, every million years, to extract heat from a mass of basalt with the area of the volcanic center and a thickness ~10 km. Thus the heat and mass budget of a volcanic center could be satisfied if the local extension rate during the volcanic episode were ~20%/m.y. (e.g., a 10-km layer of basalt drawn into a 50-km lithosphere every m.y.). This suggests that volcanic centers might have local extension rates an order of magnitude greater than the regional value. If this is so, such rapid localized extension might be viewed as the cause of the volcanic activity. As a corollary, in regions where geologic evidence implies periods of rapid local extension, intense local heating is also implied.

REFERENCES:

Bodell, John, and Chapman, D, S., 1980, Colorado Plateau heat flow (abstract): EOS, v. 61, p. 1130.

Christiansen, R. L., and McKee, E. H., 1978, Late Cenozoic volcanic and tectonic evolution of the Great Basin and Columbia intermontane regions, in Smith, R. B., and Eaton, G. P., eds., Cenozoic Tectonics and Regional Geophysics of the Western Cordillera: Geological Society of America Memoir 152, p. 283-311.

Fuis, G. S., and Allen, C. R., 1979, The southern California cooperative seismic network: U.S. Geological Survey Earthquake Information Bulletin, v. 11, p. 196-204.

Hamilton, Warren, 1980, Complexities of modern and ancient subduction systems, in Continental Tectonics [Studies in Geophysics]: National Academy of Sciences, Washington, D. C., p. 33-41.

Henyey, T. L., and Lee, T. C., 1976, Heat flow in Lake Tahoe, California-Nevada, and the Sierra Nevada - Basin and Range transition: Geological Society of America Bulletin, v. 87, p. 1179-1187.

King, P. B., and Beikman, H. M., 1974, Geologic map of the United States, scale 1:2,500,000: U.S. Geological Survey.

Lachenbruch, A. H., 1978/1979, Heat flow in the Basin and Range Province and thermal effects of tectonic extension: PAGEOPH, v. 117, p. 34-50.

Lachenbruch, A. H., and Sass, J. H., 1977, Heat flow in the United States and the thermal regime of the crust, in Heacock, J. G., ed., The Nature and Physical Properties of the Earth's Crust: American Geophysical Union Geophysical Monograph 20, American Geophysical Union, Washington, D. C., p. 626-675

Lachenbruch, A. H., and Sass, J. H., 1978, Models of an extending lithosphere and heat flow in the Basin and Range province in Smith, R. B., and Eaton, G. P., eds., Cenozoic Tectonics and Regional Geophysics of the Western Cordillera: Geological Society of America Memoir 152, p. 209-250.

Lachenbruch, A. H., Sass, J. H., Munroe, R. J., and Moses, T. H., Jr., 1976, Geothermal setting and simple heat conduction models for the Long Valley caldera: Journal of Geophysical Research, v. 81, p. 769-784.

McKenzie, Dan, 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25-32.

Morgan, Paul, Blackwell, D. D., Spafford, R. E., and Smith, R. B., 1977, Heat flow measurements in Yellowstone Lake and thermal structure of the Yellowstone caldera: Journal of Geophysical Research, v. 82, p. 3719-3732.

Reiter, M. A., and Shearer, Charles, 1979, Terrestrial heat flow in eastern Arizona, a first report: Journal of Geophysical Research, v. 84, p. 6115-6120.

Roy, R. F., Blackwell, D. D., and Decker, E. R., 1972, Continental heat flow, in Robertson, E. C., ed., The Nature of the Solid Earth: McGraw-Hill, New York, p. 506-543.

Sass, J. H., Blackwell, D. D., Chapman, D. S., Costain, J. K., Decker, E. R., Lawver, L. A., and Swanberg, C. A., 1981, Heat flow from the crust of the United States, Chapter 13, in Touloukian, Y. S., Judd, W. R., and Roy, R. F., eds., Physical Properties of Rocks and Minerals: McGraw-Hill, in press.

Shearer, C. R., 1979, A regional terrestrial heat-flow study in Arizona: Ph.D. thesis, New Mexico Institute of Mining and Technology, Socorro, New Mexico, 184 pp.

Smith, R. L., and Shaw, H. R., 1975, Igneous-related geothermal systems, in White, D. E., and Williams, D. L., eds., Assessment of Geothermal Resources of the United States--1975: U.S. Geological Survey Circular 726, p. 58-83.

Stewart, J. H., 1978, Basin-range structure in western North America: A review, in Smith, R. B., and Eaton, G. P., eds., Cenozoic Tectonics and Regional Geophysics of the Western Cordillera: Geological Society of America Memoir 152, p. 1-31.

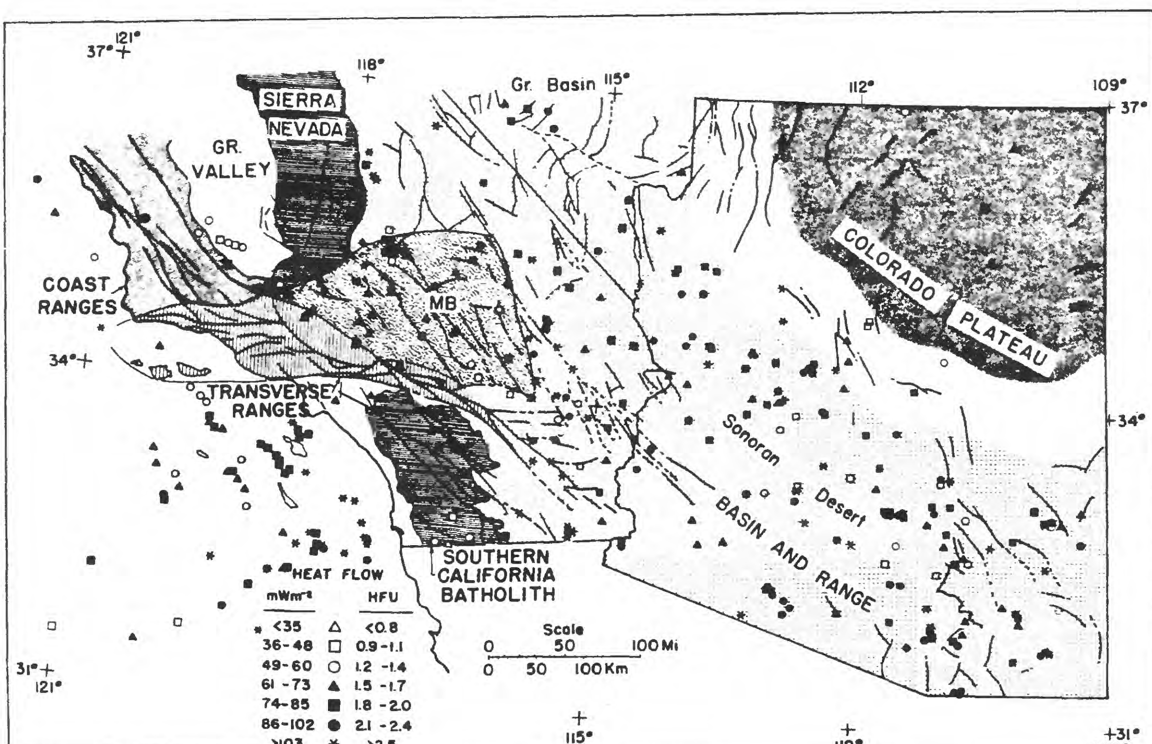

Figure 1. Major physiographic-tectonic provinces of southern California, southern Nevada, and Arizona. Generalized structure based on King and Beikman (1974). Heat flows include published values (from Sass and others, 1981; Shearer, 1979) with additional preliminary USGS values. Light stippled pattern is the Basin and Range Province. MB is the Mojave Block.

GEOLOGY-ENERGY-MINERALS BIBLIOGRAPHY FOR THE CALIFORNIA DESERT CONSERVATION AREA

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The Geology-Energy-Mineral (GEM) Resources Bibliography is a computerized list of references compiled, used by and available to the geologists of the Bureau of Land Management (BLM) California Desert Plan Staff (DPS). It contains references to maps, published and unpublished reports, and contract studies. The computer programs used to manipulate this portion of the data base were written by Jack Chamberlain, DPS computer programmer, in FORTRAN and IDEA for the use on the DPS Data General Eclipse 330 computer.

The bibliography was designed to serve several purposes: 1) to provide documentation for references used in computerized files of mineral locality records; 2) as documentation of sources used by the GEM staff; 3) as a compilation of all known geologic references pertaining to the California Desert Conservation Area; 4) as a means of cross-referencing information to facilitate retrieval of information by subject, and; 5) as a source of information for BLM personnel and the public after completion of the Desert Plan. We were more successful in fulfilling the first, second, and fourth purposes than in completing the third one. The success of the fifth purpose must await future evaluation.

The first and second purposes mentioned above were met by completing data sheets for sources used by each geologist. Data sheets were also completed for additional sources such as references pertaining to the CDCA but not used directly by the GEM staff. These include abstracts of papers given at Geological Society of America meetings, and references cited by GEM contractors. All references were used directly by the GEM staff are contained in the GEM bibliography, however, it is probable that additional sources were perused by the staff, but due to lack of time were not included in the bibliography.

The third purpose was to compile all geologic references pertaining to the CDCA. The GEM bibliography is probably the most complete catalogue of references on the geology of the CDCA but it does not contain all pertinent references. It is hoped that future additions will make the bibliography more complete and hence more useful. Final completion can never be accomplished because reports on the GEM resources of the CDCA will continue to be written.

References in the GEM bibliography can be retrieved on any one of the following items: author (any one author, it need not be the first author of a multi-authored paper to retrieve the reference), any location, category, or keyword. For instance, the user could enter SAMPSON, an author, or PICACHO, a location, or GOLD, a keyword. Paper copies or screen displays of the information requested are available in two formats. The shorter version gives a standard bibliographic reference except the computer lists authors of multi-authored papers in alphabetical order. The longer version lists everything on the data sheet including all pertinent locations and keywords.

The original intention was to make computerized bibliographic data retrievable on several variables at once. In other words, a user could request information on "Calico" and "silver" to learn what references were available on silver in the Calico Mining District. This type of cross-referenced retrieval is not available at this time. The data base is being transferred to BLM Honeywell computer in Denver and it is hoped that more complex retrievals can be achieved on that system in the future.

The preceding description of the GEM bibliographic system could be adapted to other resources.

THE VARIABILITY OF "MESOZOIC SEDIMENTARY ROCKS" IN NORTHERN YUMA COUNTY, WESTERN ARIZONA

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Extensive areas of western Arizona are mapped as "Mesozoic Sedimentary Rocks" on the Geologic Map of Arizona (Wilson, Moore, and Cooper, 1969) (Figure 1). A reconnaissance of exposures of this unit in northern Yuma County revealed that outcrop appearance is highly variable as a consequence of major variations in lithologic composition and degree of metamorphism (Marshak, 1979). To emphasize this variability, lithologic summaries of selected exposures are presented below. The rock names given are field names.

Dome Rock Mountains: Most of the southern half of this range was mapped by Wilson and others (1969) as "Mesozoic Sedimentary Rocks". An approximately 5000 m thick section of mildly metamorphosed sedimentary rocks is exposed in this area (Marshak, 1980). The lower portion of this section is composed predominantly of calcareous quartz sandstone, quartzite, maroon phyllite, and conglomerate (with quartzite and limestone clasts). Higher in the section, the predominant lithologies are greywacke, grey phyllite, and polycomponent conglomerate (which includes granitic clasts). The sedimentary section structurally overlies volcanic and volcanoclastic terranes, generally dips homoclinally southeast, and is cut by north-dipping cleavage. The sedimentary section of the Dome Rock Mountains is very similar to one described by Harding (1980) and Robison (1980) in the nearby Livingston Hills.

The Geologic Map of Arizona shows a small area of "Mesozoic Sedimentary Rocks" at the northern end of the range. This exposure is composed of metamorphic rocks including biotite schist, augen gneiss, quartzite, and marble.

Little Harquahala Mountains: The area mapped as "Mesozoic Sedimentary Rocks" in this range includes two distinctive sequences. The first is composed of interbedded maroon quartzite, maroon silty shale, and limestone. The second is composed of maroon quartzite conglomerate (with cobble to small boulder sized quartzite clasts), green-grey polycomponent conglomerate (with quartzite, limestone, conglomerate, and arkose clasts), feldspathic quartz sandstone, and mudstone. Ripple marks, cross-beds, mudcracks, and raindrop impressions occur widely in the second sequence.

Granite Wash Mountains: The metamorphic grade of lithologies mapped as "Mesozoic Sedimentary Rocks" increases from southwest to northeast (up-section) in this range. For purpose of discussion, the exposed sequence is divided into four units (A-D). Unit A, the base of the sequence, is composed of unmetamorphosed locally conglomeratic greywacke and silty shale. Load casts, graded beds, and rip up clast conglomerate locally occur in this unit. Unit B is composed of interlayered biotite-quartz-feldspar schist, phyllite, siliceous limestone, and amphibole-chlorite-quartz-plagioclase schist. Unit C is composed of quartz-sericite schist and fault-bounded outcrops of amphibole-chlorite-quartz-plagioclase schist. Unit D is composed of coarse-grained augen gneiss, and fine-grained biotite gneiss that has well developed compositional banding. A 1 m thick layer of marble crops out near the top of the unit. Unit D is intruded by small diorite plugs.

Plomosa Mountains: The area mapped as "Mesozoic Sedimentary Rocks" in this range is composed predominantly of biotite gneiss. Mineralogical and textural characteristics vary from layer to layer. Interlayered with the gneiss are layers of quartzite and phyllite. Also within the area mapped as "Mesozoic Sedimentary Rocks" is a fault bounded block of intensely deformed marble and quartzite (lithologies which resemble rocks mapped as Paleozoic strata in nearby areas) and an extensive terrane of granite with roof pendants of biotite gneiss.

This work was conducted while the author was a student at the University of Arizona. Financial and logistical support provided by the Arizona Bureau of Geology is gratefully acknowledged.

REFERENCES

Harding, L. E., 1980, Petrology and tectonic setting of the Luvingston Hills Formation, Yuma County, Arizona: Ariz. Geol. Soc. Digest, v. XII, p. 135-145.

Marshak, R. S., 1979, A reconnaissance of Mesozoic strata in northern Yuma County, Southwestern Arizona: M.S. thesis, Univ. of Arizona, Tucson.

Marshak, S., 1980, A preliminary study of Mesozoic Geology in the Southern Dome Rock Mountains, Southwestern Arizona: Ariz. Geol. Soc. Digest, v. XII, p. 23-133.

Robison, B. A., 1980, Description and analysis of Mesozoic "Red Beds", Western Arizona and Southeastern California: Ariz. Geol. Soc. Digest, v. XII, p. 147-154.

Wilson, E. D., Moore, R. T., and Cooper, J. R., 1969, Geologic Map of Arizona.

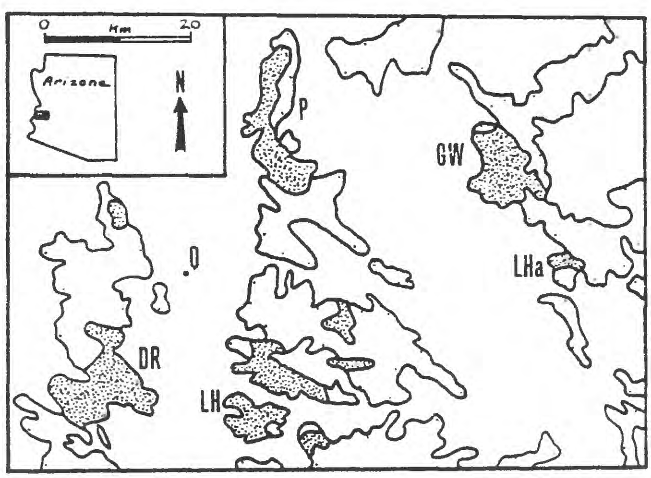

FIGURE 1: Location Map. Shaded areas are "Mesozoic Sedimentary Rocks" after Wilson and others (1969). DR = Dome Rock Mts., GW = Granite Wash Mts., LH = Livingston Hills, P = Plomosa Mts., LHa = Little Harquahala Mts., O = Town of Quartzsite.

K-AR DATING IN THE BIG MARIA MOUNTAINS, LITTLE MARIA MOUNTAINS, AND PALEN PASS AREA, RIVERSIDE COUNTY, CALIFORNIA.

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Over 50 K-Ar apparent ages of complexly-folded, metamorphosed Precambrian and Mesozoic rocks in southeastern California were recently determined. These ages are clustered in two major time intervals, 64-54 m.y.b.p., and 45-38 m.y.b.p., suggesting resetting of the K-Ar clock due to two distinct thermal or tectonic events. Effects of the younger event are thus far seen only in the Big Maria Mountains. In contrast, metamorphic rocks in the Little Maria Mountains and Palen Pass area give isotopic ages which range from 70-60 m.y.b.p.. Such ages seemingly reflect a relationship to Laramide tectonism and/or plutonism.

Apparent ages of Mesozoic and Precambrian rocks in the Big Maria Mountains fall within both time intervals. Mesozoic metasedimentary rocks, however, record the effects of the mid-Tertiary event to a greater degree than the Mesozoic intrusive rocks or Precambrian basement gneisses. This is possibly due to several factors: the metasedimentary rocks are more susceptible to resetting as a result of a higher porosity, more highly fractured character, a greater percentage of hydrous minerals, lesser degree of induration, less stable mineral assemblages, and differing overall chemical composition. Effects of the mid-Tertiary event are not restricted to the metasedimentary rocks, however, as the apparent ages of some basement gneisses also show a partial resetting during this time. Mid-Tertiary resetting was most intense in the eastern portion of the Big Maria Mountains, as demonstrated by a well-defined decrease in isotopic ages from northwest to southeast within the range.

Investigations are presently underway to determine the significance of these preliminary results in connection with thermo-tectonic events previously studied in the Whipple Mountains (Davis and others, 1980). K-Ar isotopic studies in this range (Martin and others, 1980) show that 1) the Whipple Mountain detachment surface delineates two isotopic age clusters. The upper-plate crystalline rocks show a cluster of Jurassic ages, whereas the lower-plate crystalline rocks give isotopic ages of Cretaceous to mid-Tertiary; 2) a thermo-tectonic event is related to the development of the Whipple Mountain detachment surface, and produces a gradational increase of isotopic ages with depth away from the detachment surface. Preliminary isotopic studies on the prolongation of this detachment surface in the southern Riverside Mountains also seems to show a difference of age between upper-plate and lower-plate rocks, but without the degree of secondary thermo-tectonic resetting demonstrated in the Whipple Mountains.

Field studies by Carr and Dickey (1980) in the Riverside Mountains show the detachment fault dipping gently to the south. A southerly projection of this fault intersects the northeastern portion of the Big Maria Mountains (Quien Sabe Point), where field studies by Hamilton (1964) show the presence of a "gravity thrust fault." The location and form of this low-angle fault seems to suggest that detachment faulting may be present to some extent in the Big Maria Mountains.

Research is presently underway to unravel the rather complex sequence of events involving Jurassic, Cretaceous, and Tertiary thermal/tectonic/metamorphic events together with effects of mid-Tertiary detachment faulting. We do know that the resetting of the isotopic ages below the Whipple Mountain detachment fault is not the result of a heat source at depth. Similarly, in the Big Maria Mountains, rocks which were reset by the mid-Tertiary event lie structurally and stratigraphically above partially-reset rocks which yield older isotopic ages. Whether this resetting is in any way connected with detachment faulting or not is the subject of continuing field, structural, and isotopic studies.

References

Carr, W. J., and Dickey, D. D., 1980, Geologic map of the Vidal, California, and Parker SE, California-Arizona Quadrangles: U.S. Geol. Survey Geol. Quad. Map I-1125.

Davis, G. A., Anderson, J. L., Frost, E. G., and Shackelford, T. J., Mylonitization and detachment faulting in the Whipple-Buckskin-Rawhide Mountains terrane, southeastern California and western Arizona: Cordilleran Metamorphic Core Complexes, Geol. Soc. America Memoir 153, pp. 79-129.

Hamilton, W., 1964, Geologic Map of the Big Maria Mountains NE Quadrangle, Riverside County, California and Yuma County, Arizona: U.S. Geol. Survey Geol. Quad. Map GQ-350.

Martin, D. L., Barry, W. L., Krummenacher, D., and Frost, E. G., 1980, K-Ar dating of mylonitization and detachment faulting in the Whipple Mountains, San Bernardino County, California, and the Buckskin Mountains, Arizona: Geol. Soc. America Abstracts with Programs, vol. 12, no. 3, p. 118.

MIOCENE VOLCANIC ROCKS OF THE AJO RANGE, SOUTH-CENTRAL ARIZONA

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The Ajo Range is part of a large mid-Tertiary volcanic field in south-central Arizona. Early to middle Miocene volcanic rocks, cogenetic intrusive rocks, and subordinate sedimentary rocks comprise most of the range. The bedded volcanic and sedimentary units rest unconformably on a basement of Late Cretaceous and early Tertiary granite and gneiss. The volcanic stratigraphy within the Ajo Range consists of a basal unit of Childs Latite (Gilluly, 1946), a middle unit of rhyolitic flows and tuffs, and an upper unit of basaltic and andesitic flows. This tripartite sequence has a total preserved stratigraphic thickness of approximately 1,200 m, and is part of a much more varied stratigraphy in the surrounding volcanic field.

The Childs Latite is a distinctive augite latite characterized by coarse plagioclase phenocrysts up to 4 cm long. It crops out in more than a dozen mountain ranges over an area of several thousand square kilometers. The thickest section occurs in the Ajo Range where the latite has a maximum thickness of 500 m. Throughout most of the range the Childs Latite unconformably overlies granitic basement, however, at the northern end of the range, a sequence of conglomerate and sandstone with sparse interbedded basalt flows is present between the latite and the basement rocks. The Childs Latite typically consists of gray to reddish-brown, evenly bedded flows and flow breccia, 5 to 20 m thick. Throughout the range, the flows are cut by north-trending subvertical dikes of similar composition and texture. In the Gunsight Hills at the north end of the Ajo Range, the latite occurs as thick flows that originated from domelike plugs. In the central Ajo Range, the flows are intruded by a cogenetic, subvolcanic quartz monzonite porphyry pluton. This are was apparently an eruptive center for the Childs Latite where a contemporaneous and consanguineous pluton shallowly intruded its overlying volcanic cover. In the southern Ajo Range, and in the ranges to the south, subordinate interbedded flows of olivine basalt, andesite, and dacite are locally present, along with minor interbeds of conglomerate and sandstone.

The middle rhyolitic unit of the volcanic sequence consists of gray to red, short and thick flow-banded rhyolite and rhyodacite flows, and yellow, massive to bedded, commonly crossbedded lithic lapilli and crystal-lithic rhyolitic tuffs. Complex spatial and stratigraphic relations exist between individual flows and tuffs as the tuffs were locally shouldered aside and folded during extrusion of the viscous flows. Diagenetic zeolite alteration commonly is pervasive in the tuffs and outer margins of the flows. North-trending black vitrophyre dikes intrude and are related to the flows and tuffs. Quartz, plagioclase, and biotite are the prevalent phenocrysts in the rhyolitic rocks. Sparse hornblende phenocrysts have been noted in some flows. Subordinate rock types include gray biotite rhyolite domes, olivine basalt flows, thin sheetlike dacite flows, and minor welded tuff.

Basalt and andesite flows and flow breccia unconformably overlie both the Childs Lattie and the rhyolitic unit. Appearance, texture, and composition of these flows are quite varied. Exposed thicknesses vary from several tens of meters to more than 100 m, and separate flows range from 5 to 15 m thick. Individual flows are typically light to dark gray, dense to vesicular, and porphyritic to microcrystalline. Phenocrysts include plagioclase and various combinations of olivine, calcic augite, hypersthene, hornblende, and, rarely, biotite. Olivine-augite basalt is perhaps the most abundant type of flow present, but hornblende andesite is also common. Discontinuous lenses of conglomerate are interbedded with the volcanic rocks.

The latite and rhyolite units dip 10 to 35^{o} to the east, with successively younger flows dipping less steeply eastward, possibly implying concurrent tilting and volcanism. Basalt and andesite flows overlie the latite and rhyolite flows with a slight angular discordance and dip shallowly eastward. This tilting predates the major period of Basin-and-Range normal faulting (Shafiqullah and others, 1980), which is responsible for the present physiography and fault-block shape of the Ajo Range.

K-Ar isotopic geochronology in progress (R. M. Tosdal and R. J. Miller, unpub. data) on samples from these three volcanic units, and other published K-Ar dates (Eberly and Stanley, 1978; Shafiqullah and others, 1980) indicate that volcanism took place during a period of about 6 m.y. in early to middle Miocene time. The Childs Latite, including the cogenetic subvolcanic pluton, ranges in age from approximately 20 to 17 m.y., although elsewhere it may be as old as 22 m.y. This widespread unit appears to be regionally diachronous. The rhyolitic flows and tuffs were erupted from 18 to 16 m.y. and were closely followed by basaltic flows from 16 to 14 m.y.

References

Eberly, L. D., and Stanley, T. B., Jr., 1978, Cenozoic stratigraphy and geologic history of southwestern Arizona: Geological Society of America Bulletin, v. 89, p. 921-940.

Gilluly, James, 1946, The Ajo mining district, Arizona: U.S. Geological Survey Professional Paper 209, 112 p.

Jones, W. C., 1974, General geology of the northern portion of the Ajo Range, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 77 p.

Shafiqullah, M., Damon, P. E., Lynch, D. J., Reynolds, S. J., Rehrig, W. A., and Raymond, R. H., 1980, K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas: Arizona Geological Society Digest, v. 12, p. 201-260.

THE STRUCTURE AND STRATIGRAPHY OF MIOCENE VOLCANIC ROCKS IN THE WOODS MOUNTAINS AREA, EASTERN MOJAVE DESERT, SAN BERNARDINO COUNTY, CALIFORNIA

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A large Miocene volcanic center in the Woods and Hackberry Mountains area of the eastern Mojave Desert consists of a thick sequence of generally flat-lying rhyolitic flows, domes, tephra and volcaniclastic beds, and scattered funnel-like intrusives. Consanguinous remnants of a plateau-forming ignimbrite extend 20 to 25 km north, west and south of it. The volume of the ignimbrite previous to erosion was 30 to 50 km^3. Lithic-fragment dispersal patterns suggest that venting of the ignimbrite-forming pyroclastic flows occurred at least in part in the western Woods Mountains. Additional geological and geophysical data suggest that the venting was accompanied by the formation of a shallow caldera centered in the eastern Woods Mountains.

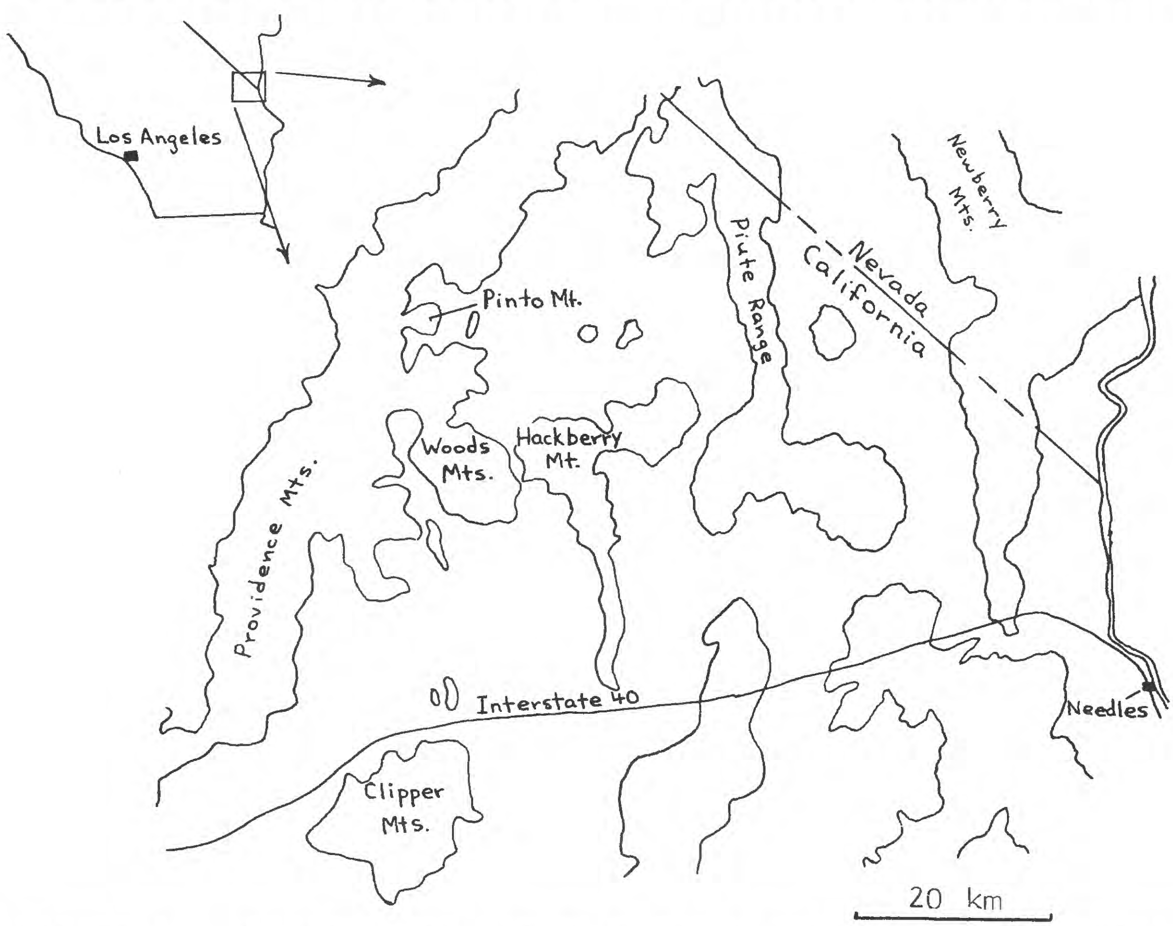

Figure 1. Generalized map of bedrock exposures in the eastern Mojave Desert

The silicic volcanic center is approximately 11 m. y. old, based on a K-Ar date on a rhyolite flow (E. H. McKee, personal communication, 1980). The volcanic rocks were deposited on a rugged erosional surface cut into pre-Tertiary crystalline rocks. Locally they overlie fossiliferrous sediments and air-fall tuff of late Barstovian to Clarendonian age (R. E. Reynolds, personal communication, 1980), consistent with radiometric ages of overlying and underlying volcanic rocks, and older volcanic rocks. One of the older volcanic rock units has been dated at 18 m. y. (E. H. McKee, personal communication, 1977). The silicic volcanic rocks are locally overlain, in the western Woods Mountains and Pinto Mountain area, respectively, by basalt and hornblende andesite.

Thick sequences consisting of andesitic flows, breccia, and tephra occur nearby to the east and south of the Woods Mountains in the Piute Range and Clipper Mountains, respectively (Figure 1). These rocks have not been dated and have not been seen in contact with the silicic rocks. However, they are believed to be older than these rocks based mainly on a relatively high degree of erosion, their intermediate composition, and in the case of the Piute Range, a strong north-south trend. Rocks in the Piute Range may be correlative with the 14.5 - 20 m. y. old Patsy Mine volcanics (cf. Anderson, and others, 1972; Anderson, 1977) that are exposed 20 km to the northeast in the Newberry Mountains (Volborth, 1973).

Most observations are consistent with a transition from intermediate to "fundamentally basaltic" volcanism, this transition having occurred sometime between 18 m. y. and 11 m. y. before present (cf. Christiansen, and Lipman, 1972). However, the occurrence of "late" andesite is unexplained; similar observations have been made in the Cady Mountains region of the central Mojave Desert (A. Glazner, personal communication, 1980). Work is being continued to determine whether the basalt exposed in the western Woods Mountains has chemical affinities similar to the mafic member of other bi-modal volcanic suites, and to determine the age of these basalts.

ACKNOWLEDGEMENTS

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REFERENCES

Anderson, R. E., 1977, Composite stratigraphic section of Tertiary rocks in the Eldorado Mountains, Nevada: U. S. Geological Survey Open File Rept. 77-483, 5p.

Anderson, R. E., Longwell, C. R., Armstrong, R. L., and Marvin, R. F., 1972, Significance of K-Ar ages of Tertiary rocks from the Lake Mead region, Nevada-Arizona: Geol. Soc. America Bull., v. 83, p. 273-288.

Christiansen, R. L. and Lipman, P. W., 1972, Cenozoic volcanism and plate-tectonic evolution of the western United States. II. Late Cenozoic: Phil. Trans. R. Soc. Lond. A, v. 271, p. 249-284.

Volborth, A., 1973, Geology of the granite complex of the Eldorado, Newberry, and northern Dead Mountains, Clark County, Nevada: Nevada Bureau of Mines and Geology, Bull. 80, 40 pp.

CORDILLERAN PERALUMINOUS GRANITES: AN ANCIENT QUARTZOFELDSPATHIC SOURCE

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Introduction. Strongly peraluminous granitoids are those which contain one or more minerals more aluminous than biotite. Such granites are very rare in the continent margin batholiths of the West, but numerous plutonic complexes to the inland are characterized by the presence of the high-Al mineral muscovite. The purpose of this paper is to summarize briefly the nature and distribution of strongly peraluminous granites (SPG) in western North America (see Miller and Bradfish, 1980, for a more complete description) and to discuss constraints upon their origin.

Distribution and Nature. SPG constitute at least 20% of the Phanerozoic plutonic rock inland from the Coast Ranges, Sierra Nevada, and Peninsular Ranges batholiths. They are concentrated in a relatively narrow belt (Fig. 1) which stretches

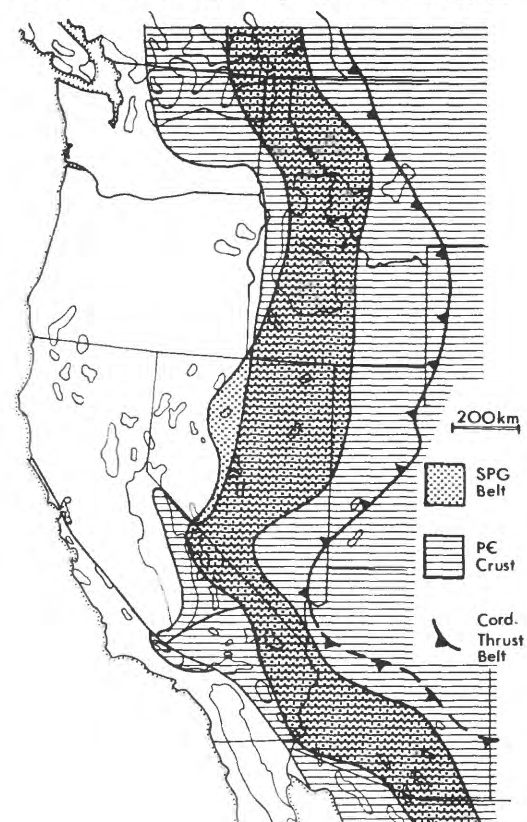


Figure 1. Phanerozoic SPG belt; margin of ancient craton (inferred from Sr isotopes; Kistler and Peterman, 1978, Armstrong et al., 1977) and foreland of Cordilleran thrust belt (Drewes, 1978) for comparison.

from Sonora to British Columbia and includes much of the Mojave and Sonoran Deserts. This belt lies at the western margin of the ancient craton and is spatially indistinguishable from a belt of Phanerozoic regional metamorphism which includes the Cordilleran metamorphic core complexes (Davis and Coney, 1979). It is parallel to and just oceanward from the foreland of the Cordilleran thrust belt.

The SPG are characterized by primary-looking phengitic muscovite. Aluminum-rich biotite is almost ubiquitous, and garnet is commonly present in trace amounts. The rocks are uniformly felsic, typically high SiO_2(>70 wt.%) granodiorites and monzogranites. Na_2O and K_2O are subequal and total about 7-9%. Initial $^{87}Sr/^{86}Sr$ ratios are distinctly higher than those of the coastal batholiths, ranging from 0.709 to 0.734. Values of $\delta^{18}O/^{16}O$ are also higher than in the coastal granitoids, ranging from about 9‰ to 13‰ (Solomon and Taylor, this volume; Ghent et al., 1979). Preliminary data acquired by Farmer indicate that $^{143}Nd/^{144}Nd$ ratios are very low (e.g. Kern Mountains, Nevada SPG ϵ_{Nd} = -19, Farmer and DePaolo, 1980).

Most of the plutons are smaller than 200km^2, but SPG complexes total more than 5,000 km^2 in northeastern Washington and northern Idaho and in the Idaho batholith. Ages range from about 20 to 160 m.y.; at least on a large scale no consistent regional pattern of emplacement ages is apparent.

Possible Origins of SPG. Many mechanisms have been proposed for the generation of SPG magmas. Mechanisms can be divided into those which consider the excess Al to be inherited from a high-Al source, and those which attribute it to incongruent crystal-liquid reactions which produce aluminous liquids in equilibrium with low-Al minerals. Reactions have even been postulated which would yield strongly peraluminous liquids from mafic to ultramafic sources (e.g. Kushiro and Yoder, 1972; Helz, 1976), but such models appear inapplicable to the Cordilleran or other typical SPG with high $^{87}Sr/^{86}Sr$ and $\delta^{18}O/^{16}O$. More reasonable are suggestions that SPG magmas are derived from quartzofeldspathic sources and attain their high Al from reactions such as: (1) liquid → hornblende + high Al liquid, or (2) high Al biotite → low Al biotite + high Al liquid. Such reactions may occur either during crystallization of a parental magma (Cawthorn and Brown, 1976) or during anatexis (Miller and Stoddard, 1980).

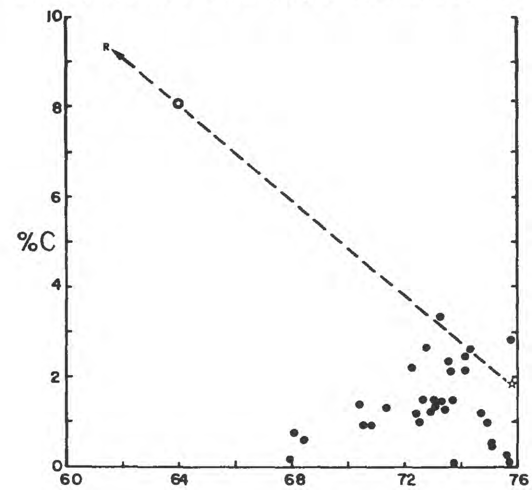
Many workers consider SPG, particularly those with high $^{87}Sr/^{86}Sr$ and high $\delta^{18}O/^{16}O$, to be S-type granites inheriting their high Al via anatexis from a pelitic sedimentary source. Although few SPG (and none of the Cordilleran examples) meet all of Chappell and White's (1974) criteria for S-type origin, it is appealing to attribute many of the compositional characteristics common to most SPG to the chemical effects of weathering on a sedimentary source material.

Imprint of a Pelitic Source? Although data are still rather limited, there is enough information available on chemistry, mineral paragenesis, and isotopic composition to evaluate the S-type model for the Cordilleran SPG.

The weathering process leaves pelitic rocks relatively high in SiO_2 and K_2O and low in Na_2O and CaO. The average pelite (cf. Shaw, 1965) metamorphosed to high grade has abundant quartz and relatively little plagioclase; depending on grade, K spar may be absent or abundant. Anatexis of such a rock will eliminate plagioclase before quartz and in many cases before K spar; thus, the magma so generated will commonly be saturated with quartz (and perhaps K spar) but not plagioclase, and therefore crystallization of plagioclase should not precede that of quartz. Non-minimum melts or crystal-rich magmas, as pointed out by Chappell and White, will be poor in Na_2O. Non-minimum melts also will be very strongly corundum-normative.

Cordilleran SPG in fact are not poor in Na_2O, and Na_2O does not decrease significantly or normative C increase in lower SiO_2 (farther from minimum) rocks (Fig. 2). Furthermore, many are characterized texturally by subhedral plagioclase which clearly began to crystallize before quartz and K spar.

Rb/Sr ratios of shales are higher than in any other major group of rocks (typically ≥1), and therefore pelitic $^{87}Sr/^{86}Sr$ increases very rapidly. Initial $^{87}Sr/^{86}Sr$ ratios of Cordilleran SPG, though high, would be consistent only with Phanerozoic pelitic sources (Fig. 3). In the cratonal setting in which these plutons were emplaced insufficient Phanerozoic



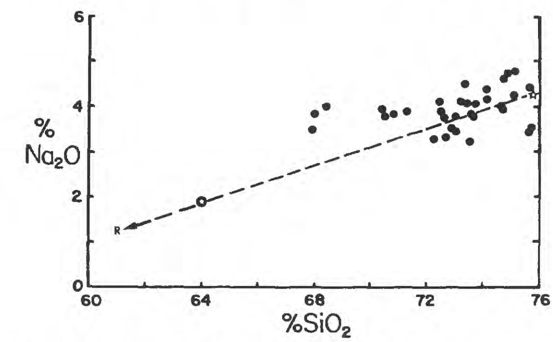


Figure 2. Na_2O and normative corundum plotted against SiO_2 for a typical SPG complex (Old Woman-Piute Range, Calif., Miller, unpubl. data). Predicted mixing lines of minimum melt (☆) and restite (R) assume average pelitic schist parent composition (✪, Shaw, 1965); crystal-charged minimum melts lie on mixing line, and non-minimum melts near it.

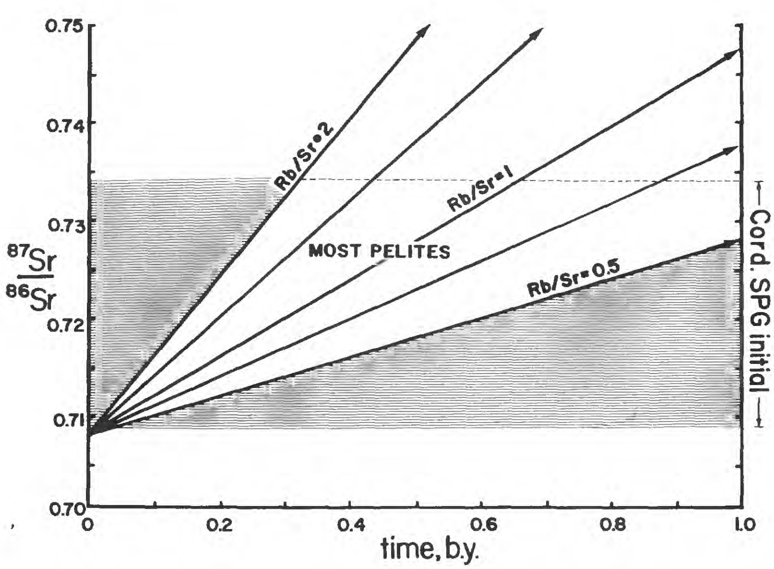


Figure 3. Range of initial $^{87}Sr/^{86}Sr$ of Cordilleran SPG, plotted against $^{87}Sr/^{86}Sr$ evolution of material with typical pelite Rb/Sr. Intersection of pelite evolution lines with Cordilleran initial ratios indicates possible relative source age.

pelite is present to account for their generation. Furthermore, Nd isotopic data of Farmer and DePaolo suggest that the source of the Kern Mountains SPG consisted primarily of ancient (model age 2.7 b.y.; certainly >1 b.y.) material, and zircon Pb from SPG in southern Arizona also documents an ancient source (Wright and Haxel, 1980). Finally, although $^{18}O/^{16}O$ values are high (Solomon and Taylor, this volume), they are lower than the values of 12-18‰ which are found in shales and metapelites (Epstein and Taylor, 1967).

The Cordilleran SPG thus do not appear to be attributable to a pelitic source.

Conclusions. The high $^{87}Sr/^{86}Sr$ and $^{18}O/^{16}O$ preclude a mafic source for Cordilleran SPG and argue against derivation from "typical" calc alkaline parental magma. The arguments presented above eliminate pelite as the principal source material. Contamination of more "typical" magma by pelitic sediment might account for the compositional distinctiveness of the SPG. A more likely mode of origin, however, involves anatexis of ancient quartzofeldspathic para- and/or orthogneiss (cf. Keith, this volume). Melting reactions in weakly metaluminous to weakly peraluminous gneisses would account for the strongly peraluminous magma compositions. Spatial restriction of the SPG to the edge of the Precambrian craton suggests either that a discontinuity in properties of the crust resulted in local development of conditions necessary for crustal anatexis, or that the nature of fusible crustal material changes abruptly at the craton edge.

References

Armstrong, R.L., W.H. Taubeneck, and P.O. Hales, 1977, Rb-Sr and K-Ar geochronometry of Mesozoic granitic rocks and their Sr isotopic compositions, Oregon, Washington, and Idaho: Geol. Soc. America Bull., v. 88, p. 397-411.

Cawthorn, R.G., and P.A. Brown, 1976, A model for the formation and crystallization of corundum-normative calc-alkaline magmas through amphibole fractionation: Jour. Geol., v. 84, p. 467-476.

Chappell, B.W., and A.J.R. White, 1974, Two contrasting magma types: Pacific Geol., v. 8, p. 173-174.

Davis, G.H., and P.J. Coney, 1979, Geologic development of the Cordilleran metamorphic core complexes: Geology, v. 7, p. 120-124.

Drewes, H., 1978, The Cordilleran orogenic belt between Nevada and Chihuahua: Geol. Soc. America Bull., v. 89, p. 641-657.

Epstein, S., and H.P. Taylor, Jr., 1967, Variation of $^{18}O/^{16}O$ in minerals and rocks: in Abelson, D.H. (ed), Researches in Geochemistry, vol. 2, New York: John Wiley, p. 29-62.

Farmer, G.L., and D.J. DePaolo, 1980, Nd and Sr isotopic evidence on the source of silicic intrusive rocks in the northern Great Basin: Geol. Soc. America, abstr. with prog., v. 12, p. 423-424.

Ghent, E.D., R.W. Kistler, and J.R. O'Neil, 1979, Petrogenesis of Mesozoic garnet-two-mica granites of the Ruby Mountains, Nevada: Geol. Soc. America, abstr. with prog., v. 11, p. 432.

Helz, R.T., 1976, Phase relations of basalts in their melting ranges at P_{H_2O} = 5kb. Part II. Melt compositions: Jour. Petrol., v. 17, p. 139-193.

Keith, S.B., 1981. Peraluminous granitoids in the Mojave-Sonoran Deserts: (this volume).

Kistler, R.W., and Z.E. Peterman, 1978, Reconstruction of crustal blocks of California on the basis of initial strontium isotopic compositions of Mesozoic plutons: U.S. Geol. Survey Prof. Paper 1071, 17 p.

Kushiro, I.S., and H.S. Yoder, 1972, Origin of the calc-alkaline peraluminous andesites and dacites: Carnegie Inst. Wash. Yr. Book, v. 71, p. 411-413.

Miller, C.F., and L.J. Bradfish, 1980, An inner Cordilleran belt of muscovite-bearing plutons: Geology, v. 8, p. 412-416.

Miller, C.F., and E.F. Stoddard, 1980, Origin of strongly peraluminous granites - a non pelitic source?: Geol. Soc. America, abstr. with prog., v. 12, p. 483.

Shaw, D.M., 1965, Geochemistry of pelitic rocks. III. Major elements and general geochemistry. Geol. Soc. America Bull., v. 67, p. 919-934.

Solomon, G.C., and H.P. Taylor, Jr., 1981, Oxygen isotopes for Mesozoic plutons and Precambrian rocks: (this volume).

Wright, J.E., and G. Haxel, 1980, Uranium-lead isotopic systematics of zircon from a garnet - and white-mica-bearing granite, Coyote Mountains, southern Arizona: Geol. Soc. America, abstr. with prog., v. 12, p. 160.

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MYLONITIC GNEISS RELATED TO EMPLACEMENT OF A CRETACEOUS BATHOLITH, IRON MOUNTAINS, SOUTHERN CALIFORNIA

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INTRODUCTION

A number of terranes in southern Arizona and southeastern California have been termed "metamorphic core complexes" (Coney, 1980). These terranes characteristically are composed of foliated and lineated mylonitic gneiss intruded by synkinematic to late kinematic granitic plutons of Cretaceous to mid-Tertiary age. In some cases the mylonitic gneiss is overlain by, and discordantly cut by, a brittle detachment zone. The age of, and physical conditions necessary for, the development of the ductile structures and mylonitic fabrics commonly are poorly understood, resulting in inadequate constraints for tectonic models. A metamorphic terrane exposed in the Iron Mountains apparently lacks Miocene detachment faulting and resetting of K-Ar ages, making it an ideal area for study of the early development of mylonitic gneiss. In this paper we describe the elements of the structural and metamorphic framework of the Iron Mountains, and present a model for the origin of the mylonitic gneiss that involves deformation above synkinematic and late kinematic diapiric plutons.

STRUCTURAL SEQUENCE

The Iron Mountains contain the easternmost exposures of the Cretaceous Cadiz Valley batholith. Rocks of the batholith range from monzogranite to granodiorite, and occupy an area greater than 1700 km^2, mainly west of the Iron Mountains (John, 1981). The margins of the batholith are not highly deformed except in the Iron Mountains, where the youngest pluton, a porphyritic monzogranite (Kgp), is foliated along its margin (Fig. 1). Overlying highly foliated plutonic rocks, interpreted as earlier phases of the batholith, include two major sills of monzogranite gneiss (Kgg) and porphyritic gneiss (Kggp) separated from the batholith by screens of Precambrian(?) gneiss. These units dip gently northwestward, so that successively higher structural units are now exposed from southeast to northwest in the range. Structural relations indicate that the two sills and the batholith proper represent a sequence of synkinematic to late kinematic intrusions that increase in age upward. Units are described below in ascending structural order.

Porphyritic monzogranite (Kgp)--Batholithic rocks forming the base of the sequence in the Iron Mountains range from monzogranite to granodiorite (Fig. 2). Typically the batholith is unfoliated and porphyritic with microcline phenocrysts set in a medium-grained, two-mica-bearing matrix. Locally within 10 to 30 m of the batholith roof, a weak foliation is acquired by the granite as a result of progressive parallel alignment of micas and ductile flattening of quartz. The batholithic rocks intrude both the overlying Precambrian(?) and monzogranite gneiss units.

Metaigneous and metasedimentary(?) rocks (p€)--The section of Precambrian(?) gneiss and sills above the batholith, 500 to 1000 m thick, is heterogeneous in composition and contains amphibolite, mafic hornblende-biotite schist, mafic diorite and granodiorite gneiss, and more felsic rocks such as granite gneiss and very fine grained, quartz-rich granite gneiss. This oldest package of the terrane is a zone of complex intrusion and deformation in which numerous generations of granite dikes are deformed and crosscut by more dikes, which are themselves deformed.

Monzogranite gneiss (Kgg)--The first sill upward is 500 to 900 m thick and is composed of approximately equigranular, leucocratic, two-mica monzogranite gneiss. The gneiss contains twinned and zoned feldspars. It is moderately foliated at its base, but deformation increases upward with the development near the top of ribbon quartz, granulation and/or recrystallization of feldspars, and recrystallization and parallel alignment of micas, resulting in textures that are definitive of what we term "mylonitic gneiss." A well-defined, WSW-trending lineation consisting of stretched quartz and elongate trains of recrystallized micas and feldspar is typical. Practically identical, but more deformed, rocks lie in a structurally higher position at the northern end of the range (Fig. 1).

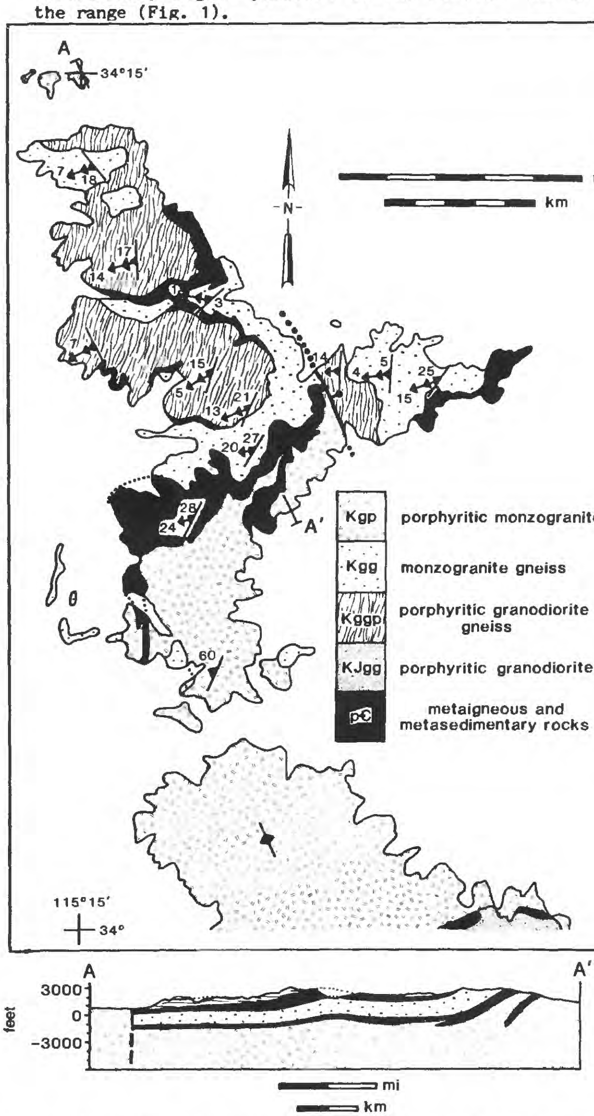


FIGURE 1. Generalized geologic map of Iron Mountains and northern part of Granite Mountains, southeastern California. Mylonitic lineations indicated by double arrow; other lineations by single arrow.

Porphyritic granodiorite gneiss (Kggp)--About 500 m of dark, porphyritic, two-mica granodiorite that is texturally a mylonitic augen gneiss overlies the monzogranite gneiss and intervening Precambrian(?) gneiss of variable (0 to 80 m) thickness. Where in contact, the porphyritic gneiss is interlayered with, and locally intruded by, the monzogranite gneiss. Dikes of foliated garnet-muscovite aplite crosscut the porphyritic gneiss. All of these units share the low-angle foliation and WSW-trending lineation. Zones of mylonite consisting of black, extremely fine-grained rock locally traverse the gneiss at shallow angles to the foliation but have the same lineation.

RELATIONS OF THE MYLONITIC GNEISS AND BATHOLITH

Deformation in the structural sequence generally increases upward, with discontinuous jumps in intensity at contacts between major lithologic units. Locally developed foliation in the top of the porphyritic monzogranite is succeeded upward by complex small folds and well developed lineations and foliations in the Precambrian(?) gneiss. Folds range considerably in orientation and are complexly refolded in most cases. "Sheath" folds with axes close to S. 70° W. trend are ubiquitous. Lineations and foliations generally parallel those in the overlying plutonic gneisses, where foliation is gently westward dipping and lineation is consistently oriented within about 10 degrees of S. 70° W. Folds were not observed in the plutonic gneisses. Crosscutting dikes in these rock units are virtually unfolded even though they are foliated, indicating that strain in the mylonitic gneiss was homogenous on a scale of hundreds of meters. Crosscutting dikes in the mylonitic gneiss strike both perpendicular and parallel to the lineation. Where thin mylonite zones cut a high-angle dike that strikes parallel to the lineation, the dike is flattened perpendicular to the boundaries of the mylonite zone. These structural features are consistent with interpretation of the lineation as a direction of extending flow. The recrystallization and plastic deformation incurred by the mylonitic gneisses and the upper part of the porphyritic monzogranite indicate that the latest strain followed emplacement and crystallization of the respective plutons.

COMPOSITIONAL AND AGE DATA

As shown in Figure 2, the modal compositions of the three major plutonic units (Kgp, Kgg, and Kggp) overlap considerably. Moreover, all contain two micas and are markedly similar to the rest of the Cadiz Valley batholith (B. John, 1981, written comm.). Chemically, these three intrusives (Fig. 3) exhibit a clear compositional affinity yet a simple comagmatic relationship is precluded. All are calc-alkalic and marginally peraluminous over a restricted range of composition (SiO_2 = 70.1 to 74.8 wt. %). Each intrusive, however, is compositionally distinct and possible differentiation trends (Fig. 3) do not follow the order of intrusion. It is probable that the three units represent melts from similar but slightly different crustal source material.

Limited age data are indicative of a late Cretaceous intrusion and deformation event. Armstrong and Suppe (1973) report K-Ar ages for two samples from the batholith: 67.3 ± 0.9 and 66.7 ± 0.9 m.y. (muscovite) and 65.6 ± 1.3 and 63.8 ± 1.2 m.y. (biotite) (recalculated with new decay constants). A K-Ar date on biotite from the monzogranite sill (Kgg) gave 65.1 ± 2.4 m.y. and a two-point Rb-Sr isochron (whole rock and biotite) from the same sample yielded an age of 60.6 m.y. (W. A. Rehrig, 1980, written comm.). These data suggest that mylonitic recrystallization was coeval with at least part of batholith emplacement.

DIAPIRIC MODEL

If the mylonitic gneiss sills are indeed early phases of the batholith, as modal and chemical compositions indicate, and mylonitization ceased at approximately the same time as the intrusion of the last batholithic phase, as suggested by age data, then the deformation must be contemporaneous with batholith emplacement. The layers of wallrock between the plutonic gneiss sills indicate that each intruded separately into country rocks, dragging screens of wallrock into position adjacent to earlier plutons. Because the gneiss units are successively more deformed both upward in the sequence and with increasing age, it is probable that each unit was deformed as subsequent plutons were emplaced. The simplest internally consistent model accounting for these relations is that of diapiric emplacement of several pulses of magma, each pulse flattening the crystallized, but still warm, roof of previously emplaced plutons. Uniformly oriented lineations in the Iron Mountains can be the result of locally homogeneous strain above a small part of a large batholith, or can be caused by strain above strongly asymmetrical, nappe-like diapirs. Relations in the Iron Mountains do not permit a choice between these alternatives.

REGIONAL RELATIONS

Latest Cretaceous intrusion of calc-alkalic, peraluminous magmas occurred in a number of metamorphic terranes in southeastern California and adjacent Arizona, including the Chemehuevi, Sacramento, Whipple, Rawhide, and Buckskin Mountains area (Davis and others, 1980; Anderson and Rowley, 1981); the Riverside, Big Maria and Little Maria Mountains area; and the Old Woman Mountains (Miller and others, 1981). The former two areas are metamorphic terranes that have many of the typical features of metamorphic "core complexes," whereas the latter is characterized by an eastward vergent nappe that formed during plutonism. The Iron Mountains are adjacent to the southern end of the Old Woman Mountains, and, like the Old Woman Mountains,

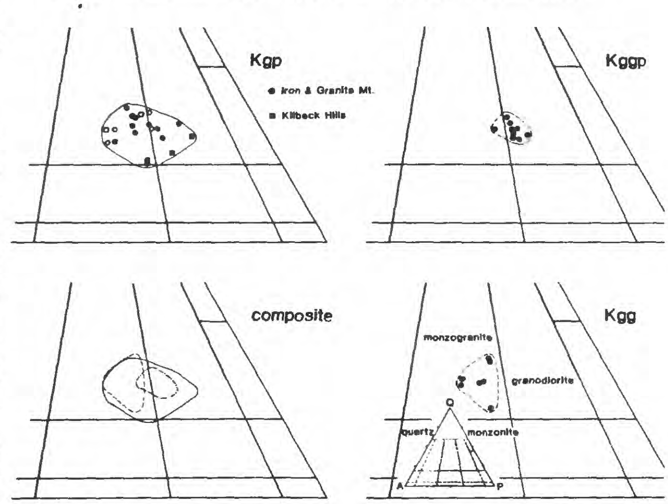
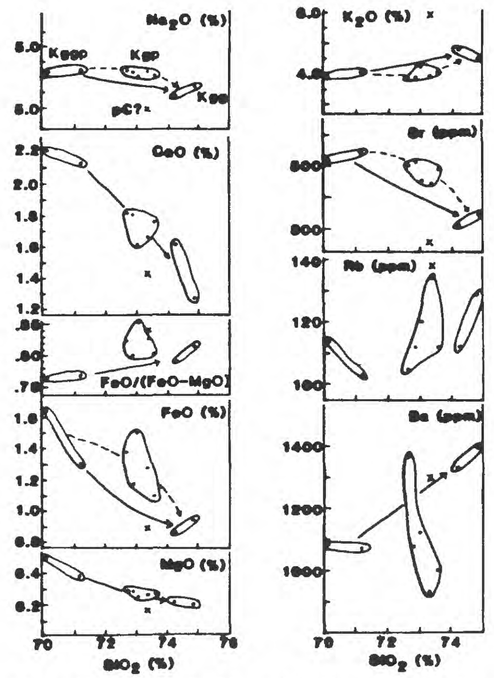


FIGURE 2. Modal analyses of granitic rocks. Open symbols for Kgp indicate equigranular rocks; closed symbols indicate porphyritic. Rocks in the Kilbeck Hills (which lie adjacent to the northern Iron Mountains) may belong to a different lineage. Modal analyses performed on stained slabs; in most cases 1000 grains were counted.



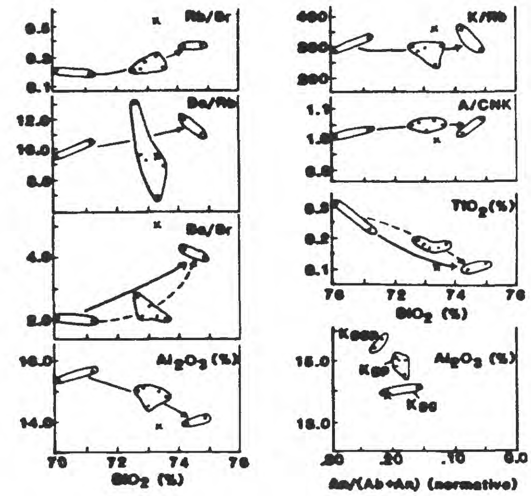


FIGURE 3. Plots of chemical analyses of major rock units. Unit names as in Fig. 1; pЄ? is foliated leucocratic monzogranite. Possible lines of magma evolution are sketched on the plots. A/CNK = $Al_2O_3/(CaO+Na_2O+K_2O)$ on a molar basis.

have little evidence for Tertiary development of mylonitic rocks or detachment surfaces. These western examples of metamorphic terranes, which lack the Tertiary features of "core complexes," may therefore belong in a less complicated tectonic regime than the eastern terranes. However, all of the terranes have a common lineation orientation in the mylonitic rocks and a peraluminous character in the intrusive rocks.

We consider that relations in the Iron Mountains demonstrate a close relationship between pluton emplacement and formation of mylonitic gneiss. The regionally uniform orientation of the mylonitic lineation, and a lack of batholiths related to some of the mylonitic terranes, require a regionally operative dynamic system. An attractive possibility is eastward flow from an axial zone of crustal thickening along the batholithic belt. Relations in the Old Woman Mountains indicate eastward-directed shear during late Cretaceous time, leading Howard and others (1980) to suggest that the strain resulted from thrust belt deformation, as originally postulated by Burchfiel and Davis (1975). If so, the Iron Mountains may represent batholith emplacement in asymmetric nappe-like bodies linked to development of nappes and low-angle faults in crystalline rocks in a thrust belt east of the batholith. Details of the relations between batholith emplacement, mylonitic gneiss formation, and development of nappes and low-angle faults in the Iron and Old Woman Mountains may provide valuable clues to the nature of the link between magmatism and thrust belt development in the eastern Mojave Desert area.

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REFERENCES

Anderson, J. L., and Rowley, M. C., 1981, Synkinematic intrusion of peraluminous and associated metaluminous granitoids, Whipple Mountains, California: Can. Mineral., v. 19, (in press).

Armstrong, R. L., and Suppe, J., 1973, Potassium-Argon geochronometry of Mesozoic igneous rocks in Nevada, Utah, and southern California: Geol. Soc. Amer. Bull., v. 84, p. 1375-1392.

Burchfiel, B. C., and Davis, G. A., 1975, Nature and controls of Cordilleran orogenesis, western United States: Extensions of an earlier synthesis: Amer. Jour. Science, v. 275-A, p. 363-396.

Coney, P. J., 1980, Cordilleran metamorphic core complexes: An overview: In: Crittenden, M. D., Jr., and others, eds., Geol. Soc. Amer. Memoir 153, p. 7-31.

Davis, G. A., Anderson, J. L., Frost, E. G., and Shackelford, T. J., 1980, Mylonitization and detachment faulting in the Whipple-Buckskin-Rawhide Mountains terrane, southeastern California and western Arizona: In: Crittenden, M. D., Jr., and others, eds., Geol. Soc. Amer. Memoir 153, p. 79-129.

Howard, K. A., Miller, C. F., and Stone, P., 1980, Mesozoic thrusting in the eastern Mojave Desert, California: Geol. Soc. Amer. Abstr. Prog., v. 12, p. 112.

John, B. E., 1981, Reconnaissance study of Mesozoic plutonic rocks in the Mojave Desert region: In: Howard, K.A., and others, eds., U.S. Geol. Survey Open-file Report 81-503, p. 48-50.

Miller, C. F., Stoddard, E. F., Bradfish, L. J., and Dollase, W. A., 1981, Composition of plutonic muscovite: Genetic implications: Can. Mineral., v. 19, (in press).

THE SONOMA OROGENY IN THE MOJAVE DESERT ?

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Roof pendants in the southwestern Mojave Desert near Victorville, CA, and in the San Bernardino Mountains, CA, contain platform and marginal miogeoclinal strata of late Precambrian and Paleozoic age that are correlative with sequences in the eastern Mojave Desert (Stewart and Poole,1975; Cameron, 1980; Burchfiel and Davis, 1981; Miller, in press). In addition, Triassic(?)-Jurassic sedimentary rocks are also similar across this terrane (Miller and Carr, 1978; Cameron and others, 1979), suggesting paleogeographic continuity between these two parts of the Mojave Desert since the Precambrian.

Near Victorville, miogeoclinal/platform strata were multiply deformed, metamorphosed to greenschist grade, and intruded by monzonite plutons interpreted to have a minimum age of 233 $\pm$ 13 m.y. (Miller and Sutter, in press). The Triassic or Jurassic Fairview Valley Formation unconformably overlies a monzonite pluton that intrudes Paleozoic marble and contains debris derived from the erosion of this plutonic and metamorphic terrane. The Fairview Valley Formation contains abundant clasts of Lower Permian (Wolfcampian) limestone (Bowen, 1954), demonstrating that rocks at least this young were involved in the deformation. This deformation, then, is post-Lower Permian and pre-233 $\pm$ 13 m.y., or Permo-Triassic. In the eastern Mojave Desert, strongly deformed Paleozoic miogeoclinal rocks are unconformably overlain by Triassic(?) sedimentary rocks, suggesting that Permo-Triassic deformation was not restricted to the southwestern part of the Mojave (Burchfiel and others, 1980).

Scattered exposures of strongly deformed and metamorphosed sedimentary rocks in the northwestern Mojave Desert are, at least in part, correlative with and lithologically similar to less metamorphosed eugeoclinal lower Paleozoic strata north of the Garlock fault in the El Paso Mountains. The lower Paleozoic eugeoclinal rocks of the El Paso Mountains are similar in age and lithology to rocks in the Roberts Mountains allochthon in Nevada and apparently were involved in the Late Devonian-Early Mississippian Antler orogeny (Poole, 1974; Poole and Christiansen, 1980). In contrast, platform/miogeoclinal sections in the eastern and southwestern Mojave Desert show no evidence of a mid-Paleozoic deformation; furthermore, these regions show no evidence of clastic input during the upper Paleozoic, unlike the broad region that lay to the east of the Antler highlands further north and received detritus from this belt (Poole, 1974). In addition, upper Paleozoic sequences in the northwestern Mojave, which contain minor volcanic and coarse clastic rocks, are quite dissimilar in lithology and depositional environment from coeval carbonate rocks of the eastern Mojave Desert. Thus these two parts of the Mojave apparently were not contiguous during the Paleozoic.

Isopachs and facies boundaries for miogeoclinal rocks in the Mojave strike at a high angle to the present-day contact that separates eastern and southwestern Mojave rocks from northwestern Mojave rocks, suggesting that the contact between the two terranes is a fault (Burchfiel and Davis, 1981). These data suggest that the northwestern Mojave is allochthonous and was emplaced by strike-slip faulting from the north, where we know the Antler orogeny took place (Burchfiel and Davis, 1981. These authors suggest that this occurred during a major episode of left-lateral faulting related to the much debated Permo-Triassic truncation of the continental margin.

Several lines of evidence suggest that this strike-slip event may have occurred before (or during) but not after the emplacement of the Golconda allochthon during the Sonoma orogeny in Nevada, and that the northwestern Mojave rocks were emplaced prior to (or during) Permo-Triassic or earliest Triassic deformation and plutonism in the Mojave:

1. In the Inyo Mountains, Stevens and Stanton (1980) have documented the Early Permian formation of a southeast-trending fault-bounded basin across what formerly had been a stable carbonate shelf, suggesting to them that tectonic modification of the margin may have begun in the Early Permian.
2. If lower Paleozoic eugeoclinal rocks were strike-slipped south during this time, Permian rocks which depositionally(?) overlie these in the El Paso Mountains (Dibblee, 1967) may have been (at least in part) deposited during their southward movement, as they are distinct from

upper Paleozoic rocks of the Havallah sequence in the Golconda allochthon in Nevada. The Golconda allochthon was emplaced in the earliest Triassic (Speed, 1979); and it is likely that this thrusting occurred after (or during) strike-slip movement.
3. Cox and Morton (1980) have dated plutons in the western El Paso Mountains as latest Permian or Permo-Triassic. If these rocks are part of the same plutonic belt as Early Triassic(?) plutons in the southwestern Mojave, then their intrusion most likely post-dates the final emplacement of the El Paso-northwestern Mojave eugeoclinal terrane.

The figures below depict the possibility that deformation and plutonism in the Mojave was broadly synchronous with the Sonoma orogeny in Nevada, both events perhaps being due to an episode of increased convergence between oceanic and continental plates in the Permo-Triassic. To the north, convergence caused the back arc collapse and thrusting of continental rise and marginal basin deposits of the Golconda allochthon, while to the south, deformation of the leading edge of the continent and emplacement of plutons occurred above an east-dipping subduction zone. Data from the Mojave Desert may therefore support plate tectonic models depicting east-directed subduction of oceanic rocks further north during the Sonoma orogeny. In terms of mountain-building, the "Sonoma" event in the Mojave was by far more spectacular than its counterpart to the north.

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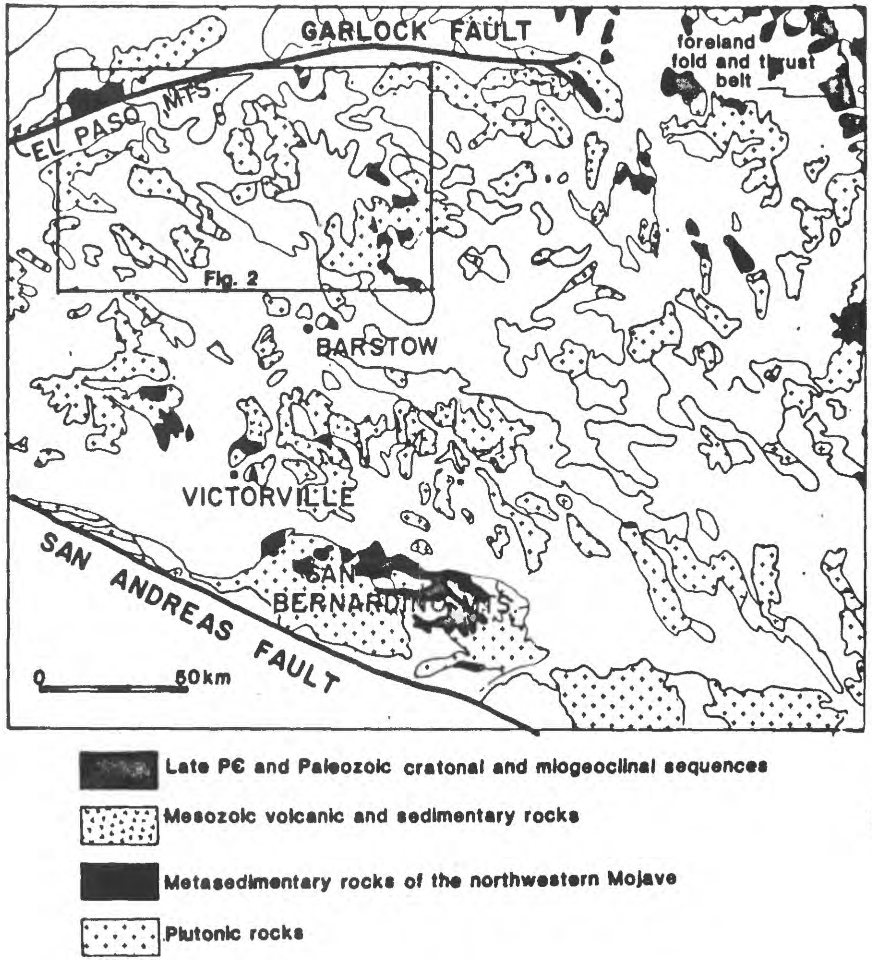
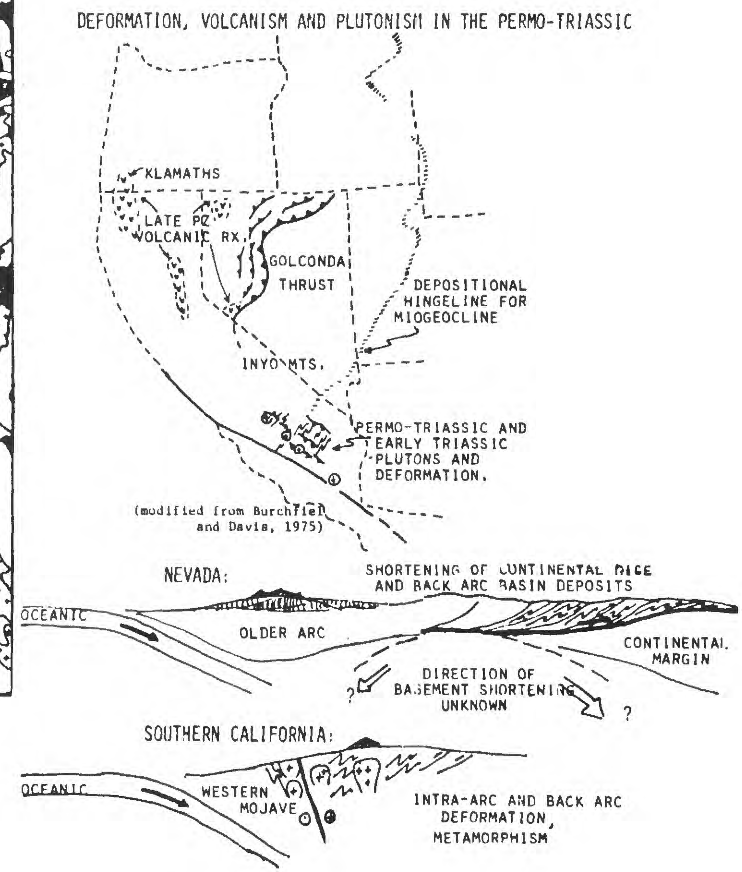
REFERENCES:

Burchfiel, B.C., and Davis, G.A., 1981, Mojave Desert and environs, in Ernst, W.G., ed., The Geotectonic development of California, Rubey Volume I, Prentice Hall, Inc., N.J., p. 217-252.
Burchfiel, B.C., and Davis, G.A., 1975, Nature and controls of Cordilleran orogenesis, western United States: Extensions of an earlier synthesis: Am. Jour. Sci. v. 272, p. 97-118.
Burchfiel, B.C., and Cameron, C.S., Guth, P.L., Spencer, J.E., Carr, M.D., Miller, E.L., and McCulloh, T.H., 1980, A Triassic overlap assemblage in northern Mojave/Death Valley region, California: An interpretation: Geol. Soc. America Abstr. w/ Prog., v. 12, no.7, p. 395.
Bowen, O.E., 1954, Geology and Mineral deposits of the Barstow quadrangle, San Bernardino County, California: California Div. Mines and Geol. Bull. 165, 208 p.
Cameron, C.S., 1980, Late Precambrian strata of the San Bernardino Mountains, California: Their relation to the Cordilleran miogeocline: Geol. Soc. America Abstr. w/ Prog., v. 12, no. 3, p.100.
Cameron, S., Guth, P.L., and Burchfiel, B.C., 1979, The early Mesozoic Cave Mountain sequence: Its implication for Mesozoic tectonics: Geol. Soc. America Abstr. w/ Prog., v. 11, no. 7, p. 397.
Cox, B.F., and Morton, J.L., 1980, Late Permian plutonism, El Paso Mountains, California: Geol. Soc. America Abstr. w/ Prog., v. 12, no. 3, p. 103.
Dibblee, T.W. Jr., 1967, Areal geology of the western Mojave Desert, California: U.S. Geol. Surv. Prof. Paper 522, 153 p.
Miller, E. L., 1981, Geology of the Victorville Region, California: Geol. Soc. America Bull. (in press).
Miller, E.L., and Carr, M.D., 1978, Recognition of Aztec equivalent sandstones and associated mid-Mesozoic metasedimentary deposits within the Mesozoic magmatic arc in the southwestern Mojave Desert, southern California, in Howell, D.G., and McDougall, K.A., eds., Mesozoic Paleogeography of the western United States: Soc. Econ. Paleont. and Meneral. Pacific Section, Pacific Coast Paleogeography Symposium 2, p. 283-290.
Miller, E.L., and Sutter, J.F., 1981, 40Ar/39Ar age spectra for biotite and hornblende from plutonic rocks in the Victorville region, California: Geol. Soc. America Bull. (in press).
Poole, F.G., 1974, Flysch deposits of the Antler foredeep, western United States, in Dickinson, W.R., ed., Tectonics and Sedimentation: Soc. Econ. Paleont. and Mineral. Special Pub. 22, p. 58-82.
Poole, F.G., and Christiansen, R.L., 1980, Allochthonous lower and middle Paleozoic eugeosynclinal rocks in the El Paso Mountains, northwestern Mojave Desert, California: Geol. Soc. America Abstr. w/ Prog., v. 12, no. 3, p. 147.
Speed, R.C., 1979, Collided Paleozoic platelet in the western U.S.: Journ. Geology, v. 87p.279-292.
Stewart, J. H. , and Poole, F.G., 1975, Extension of the Cordilleran miogeosynclinal belt to the San Andreas fault, southern California: Geol. Soc. America, v. 86, p. 205-212.
Stevens, C.H., and Stanton, W.R., 1980, Stylastraea-bearing gravity flow sequence of Early Permian age in eastern California: Geol. Soc. America Abstr. w/ Prog., v. 12, no. 3, p. 154.


GARLOCK FAULT
foreland fold and thrust belt
EL PASO MTS
Fig. 2
BARSTOW
VICTORVILLE
SAN BERNARDINO MTS.
SAN ANDREAS FAULT
0
50km
Late P€ and Paleozoic cratonal and miogeoclinal sequences
Mesozoic volcanic and sedimentary rocks
Metasedimentary rocks of the northwestern Mojave
Plutonic rocks


DEFORMATION, VOLCANISM AND PLUTONISM IN THE PERMO-TRIASSIC
KLAMATHS
LATE PZ VOLCANIC RX.
GOLCONDA THRUST
DEPOSITIONAL HINGELINE FOR MIOGEOCLINE
INYO MTS.
PERMO-TRIASSIC AND EARLY TRIASSIC PLUTONS AND DEFORMATION.
(modified from Burchfiel and Davis, 1975)
NEVADA:
SHORTENING OF CONTINENTAL RISE AND BACK ARC BASIN DEPOSITS
OCEANIC
OLDER ARC
CONTINENTAL MARGIN
DIRECTION OF BASEMENT SHORTENING UNKNOWN
SOUTHERN CALIFORNIA:
OCEANIC
WESTERN MOJAVE
INTRA-ARC AND BACK ARC DEFORMATION, METAMORPHISM

NEOTECTONICS OF ARIZONA

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Christopher M. Menges, Arizona Bureau of Geology & Mineral Technology

We recently completed a comprehensive map of Quaternary faults in the state of Arizona at a scale of 1:500,000.[1,2] The map is based on interpretation of U-2 airphotos, supported by extensive ground and aerial reconnaissance. Accompanying this map is a set of tables that describe each fault as to evidence for faulting and age of displacement, and its rank in one of three probability classes: proven, probable, and very possible. Also, we show at 1:1 million scale the areas of broad Quaternary uplift, subsidence, and warping, compiled mainly from other sources.

Antecedents of Quaternary deformation.- The Basin and Range deformation *sensu stricto* began 17-10 m.y. ago in Arizona (Shafiqullah *et al.*, 1980). Characterized by high-angle faulting, it produced the larger elements of the present topography in the Basin and Range portion of Arizona (Fig. 1), of disconnected mountain ranges and intermontane basins. In the Sonoran Desert it began 17 to 12 m.y. ago and ended 10 to 6 m.y. ago; in the Mexican Highland section, however, it began 12 to 10 m.y. ago and ended 6 - 4 m.y. ago (Shafiqullah *et al.*, 1980; Scarborough and Peirce, 1978; Eberly and Stanley, 1978). The dominant structural style is high-angle normal faulting that produced horsts and grabens with a wide range of displacements and lateral dimensions, oriented mostly northwest to north to northeast. The temporal and areal fault pattern in SE, NW, and perhaps SW Arizona suggests regional extension, initially oriented WSW and later E-W to WNW. The resulting intermontane basins contain middle to late Miocene syntectonic sediments that grade upward into relatively undeformed Pliocene deposits.

The Basin and Range deformation was followed by continued high-angle normal faulting on a much reduced, gradually diminishing, and more localized scale. In the Sonora Desert, high-angle faulting ceased in the middle Pleistocene and this area has been historically aseismic. In the Mexican Highland section and western edge of the Colorado Plateau, however, high-angle faulting continued in places into the late Pleistocene and perhaps into early Holocene.

Neotectonic deformation.- Of the several hundred Quaternary faults we have mapped in Arizona, less than 20 percent are classed as proven or probable. Most are older than 250,000 years and none are younger than 4,000 years; in all cases the definitely ruptured deposits are latest Pleistocene or older. All of these faults are normal, high-angle, and entirely or largely dip-slip (except several faults SW of Yuma, associated with the San Andreas system, that may be significantly strike-slip). The Quaternary faults have the same orientations as those of the Basin and Range deformation, mostly NE, NW, N, NNW, and WNW; the Quaternary faults probably are reactivat-

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[1] This project was supported by a U. S. Geological Survey grant (L. K. Lepley, Contractor).

[2] With us, 'Quaternary faults' should show proven, probable, or very possible displacement of Quaternary *sensu lato* (i.e., <3.2 m.y. old) deposits or landsurfaces. However, we also map a special class of possible Quaternary faults -- those few of the myriads of known faults that displace only pre-Quaternary rocks and whose geomorphology and association with known, probable, and/or very possible Quaternary faults suggests a good possibility that they may have had movement during the Quaternary.

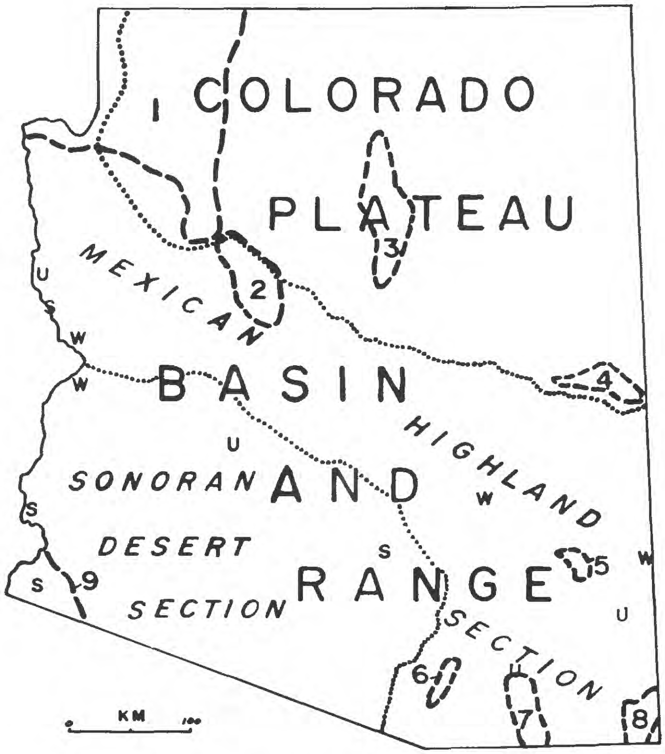

Figure 1. State of Arizona, showing physiographic divisions (dotted boundaries) and areas with concentrations of Quaternary faults (dashed boundaries; see Table 1). Single letters indicate areas of broad Quaternary uplift (U), subsidence (S), or warping (W).

Table 1. Areas of greatest concentrations of Quaternary faults in Arizona: Summary of fault characteristics.

AREA NUMBER in Figure 1 / AREA NAME	NUMBER OF QUATERNARY FAULTS X 10 (proven, probable, & very possible only)	LENGTHS (mapped, range in km; maximums in parenthesis include possible composite faults)	SCARP HEIGHTS (range in m; maximums in parenthesis include possible Pliocene displacements)	ORIENTATIONS (range; most common first)	AGE OF QUATERNARY DISPLACEMENT (maximum/ minimum age range)[3]
1. Northwestern Arizona	8.5	1 - 20	1 - 50 (425+)	NNE, NE, N, NNW, NW, ENE	e / 1 (h?)
2. Chino Valley-Skull Valley-Prescott area	1.5	2 - 30	3 - 30	NW, WNW, N, NNE	m / 1 (h?)
3. San Francisco volcanic field, eastern & southern parts	8	1 - 30	3 - 40 (120)	NW, NNW, N, NNE, NE, WNW	e / 1
4. Northern part of White Mts volcanic field	0.5	5 - 10	5 - 40 (500)	NW, NE, WNW, E-W	e / 1?
5. Piedmont south and west of Safford	1.5	1 - 10 (30)	2 - 12	NNW, N, NW	e-m / 1(?)
6. Western piedmont of Santa Rita Mountains	1	1 - 7 (40)	1.5 - 5	NE, N, ENE	e-m / 1(?)
7. Upper San Pedro Valley	2	2 - 18	2 - 15	NE, ENE, N, NNW, NW	e / 1
8. San Bernardino Valley	3	2 - 12	2 - 20 (100+)	NE, N, NNE, NNW, NW WNW, E-W	e / 1
9. Yuma basin	0.5	2 - 13	3 - 15 (60)	NW, NNW, WNW	e / 1(h?)

[3] Explanation of age symbols (m.y.a. = millions of years ago):
e = early Pleistocene (3.2 - 1.6 to 0.9 - 0.7 m.y.a.); m = middle Pleistocene (0.9 - 0.7 to ca. 0.25 m.y.a.);
1 = late Pleistocene (ca. 0.25 to 0.01 m.y.a.); h = earlier Holocene (10,000 to 4,000 years ago).

ed earlier faults. Generally the Quaternary faults are marked by scarps of 3 to 20 m height (some are >40 m high) with maximum scarp slope angles of 6° to 30°. Recurrent movements along a few faults are suggested by scarps with compound slope angles (benches), increasing scarp height and/or fault offset in progressively older deposits, and/or multiple tectonic stream terraces upstream from scarps. These terraces suggest recurrence intervals of 10^4 to 10^5 years (W. Bull and M. Sbar, Univ. Arizona, oral commun., 1980).

The greatest concentrations of Quaternary faults are in nine areas (Fig. 1, Table 1): (1) Northwestern Arizona, at and adjoining the western edge of the Colorado Plateau, especially the lower Virgin River basin, Lake Mead area, Grand Wash basin, southern St. George basin, and parts of the Hurricane and Toroweap faults; (2) Chino Valley-Skull Valley-Prescott area; (3) eastern and southern parts of the San Francisco volcanic field; (4) northern part of the White Mountains volcanic field; (5) the piedmont south and west of Safford; (6) western piedmont of the Santa Rita Mountains; (7) upper San Pedro Valley; (8) San Bernardino Valley; and (9) Yuma basin.

Quaternary faults are lacking, very rare, or not discernible in three large areas:

(A) The Colorado Plateau east of area 3 and north of area 4. Although apparently stable during the Quaternary, this area provides almost no stratigraphic or geomorphic control for detecting possible Quaternary displacements: it is mostly stripped bedrock erosion surfaces with a little late-Quaternary mantle in places.

(B) The extremely dissected high-relief area of the Mexican Highland south of the Mogollon Rim from Chino Valley to the New Mexico line. Any Quaternary faults cannot be identified because of the paucity of Quaternary deposits and erosion surfaces.

(C) The Sonoran Desert east of the Yuma basin (area 9). Widespread Quaternary deposits and landsurfaces in the broad intermontane basins of this area indicate very little Quaternary faulting.

Thirteen areas of probable or possible broad Quaternary uplift, subsidence, or warping have been identified on the basis of one or more of the following: (1) anomalous altitudes of Pliocene or Quaternary deposits or landsurfaces, (2) extensive areas of deformed Pliocene or Quaternary deposits within intermontane basins, (3) variations in altitude of the highest shoreline of a middle Pleistocene lake, and (4) modern altitude changes shown by repeated geodetic surveys.

REFERENCES CITED

Eberly, L. D., and Stanley, T. B., 1978, Cenozoic stratigraphy and geologic history of southwestern Arizona: Int. Geol. Cong., 24th, sec. 3, p. 607-616.

Scarborough, R. B., and Peirce, H. W., 1978, Late Cenozoic basins of Arizona, in Callender, J. R. and others, eds., New Mexico Geol. Soc. Guidebook, 29th field conf., p. 253-259.

Shafiqullah, M., Damon, P. E., Lynch, D. J., Reynolds, S.J., Rehrig, W. A., and Raymond, R. H., 1980, K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas, in Jenney, J. P., and Stone, C., eds: Arizona Geol. Soc. Digest, v. 12, p. 201-260.

STRUCTURAL GEOLOGY OF THE DATE CREEK BASIN AREA, WEST-CENTRAL ARIZONA

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The Date Creek basin is a northwest-trending structural and topographic low bounded on the southwest side by normal faults (ST, Fig. 1). Preserved in the basin is a thick section of Oligocene(?) to late Miocene volcanic and basin-fill sedimentary rocks, covered by a thin veneer of Pliocene to Holocene alluvium (Fig. 1). Southwest of the basin is a late Mesozoic to early Tertiary mylonitic and mid-Tertiary low-angle fault terrain. To the northeast lie Precambrian crystalline rocks typical of those of the transition zone between the Colorado Plateau and the Basin and Range Province.

A major mid-Tertiary low-angle fault (the Rawhide fault, Shackelford, 1980) exposed to the southwest of the basin appears to plunge northeasterly beneath the Date Creek basin as suggested in a seismic profile across the basin (T. Loveseth, 1980, oral commun.) and interpreted in Figure 2. Above

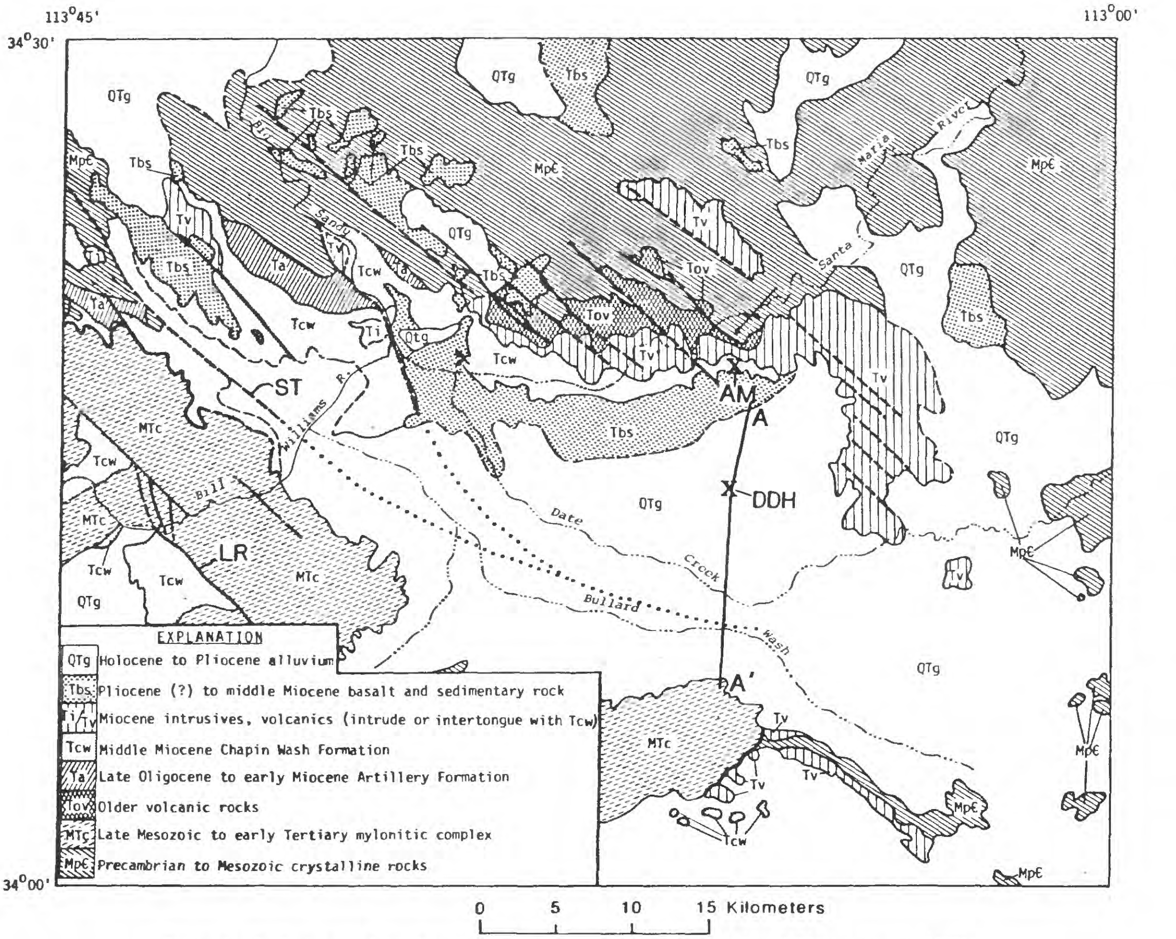

Figure 1.--Geologic map of the Date Creek Basin area. Data from Shackelford (1976), Gassaway (1977), J. Otton (unpublished mapping), and W. E. Brooks, Jr. (unpublished mapping). DDH - El Paso Natural Gas/Brown and Thorp drillhole, ST - Sandtrap Wash Fault, LR, - Lincoln Ranch Fault, A-A' - Cross-section, Figure 2.

that surface are tilted blocks composed of Precambrian crystalline rocks and Oligocene(?) sedimentary and volcanic rocks as suggested by projections of surface geology along the northern edge of the basin into the subsurface (Fig. 1), drillhole intercepts (especially DDH, Figures 1 and 2, which intercepted basement) and a Schlumberger resistivity profile (Fig. 3). These older tilted rocks include the Artillery Formation at the western end of the basin (Ta, Fig. 1) and unnamed older volcanic and sedimentary rocks in the eastern part (Tov, Fig. 1). Unconformably overlying these tilted blocks are gently dipping basin-fill sedimentary rocks and intertonguing volcanic rocks (Tv, Tcw, Tbs, Fig. 1). K-Ar ages obtained on these younger volcanic rocks and vertebrate fossil remains in the associated sediments

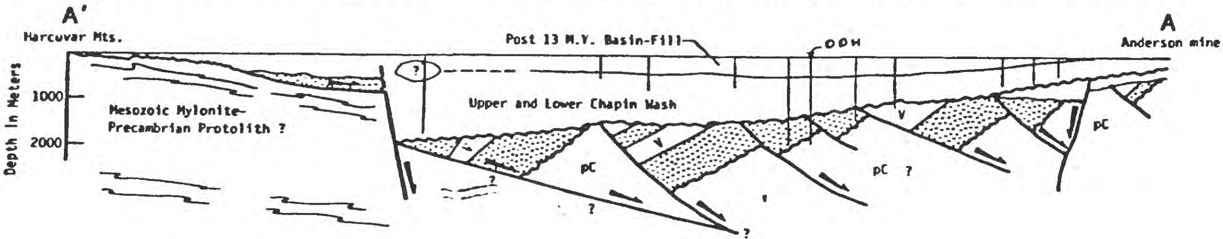

Figure 2.-- Interpretive geologic cross-section along *A-A'*.

suggest that this overlying gently tilted section ranges in age from about 26 to 9 m.y. Thus movement on the regional detachment surface must have occurred prior to 26 m.y. ago. This movement resulted in the formation of the early Date Creek basin which was filled with sediments of the Chapin Wash Formation. Movement on major normal faults continued during basin formation until abouy 9 m.y. ago. About 1 km of total dip-slip separation has occurred on the relatively high angle fault along the southwestern side of the basin (Fig. 2). This faulting has offset the detachment surface. Concurrently with Chapin Wash deposition and normal faulting, broad arching on northeasterly trending axes occurred southwest of and within the basin. The detachment surface was arched at this time. Downwarping considerably deepened the central part of the Date Creek basin.

Normal faulting and downwarping strongly influenced facies in the basin. Down to the notheast movement on a major northwest-trending normal fault zone that follows the Big Sandy River (Fig. 1) controlled alluvial and lacustrine facies relations during Chapin Wash time. Chapin Wash units are predominately alluvial in character and thin to the west across the fault and thicken and become largely lacustrine east of the fault. Algal reefs formed along the fault line where lake waters rapidly shallowed. Continued movement on this fault zone later elevated the western part of the basin and allowed erosion of the uplifted Tertiary rocks. This movement affected the lower portion of Miocene basalts and basin fill sediments which (Tbs, Fig. 1) range in age from 13 to 10 m.y., but does not appear to have affected mesa-capping basalts in the upper part of that unit dated at 9 m.y.

The latest structural feature to form in the basin area is the Lincoln Ranch fault (LR, Fig. 1), a southwesterly directed thrust which cuts the arched detachment surface in the Lincoln Ranch and Rankin Ranch basins. The age of this thrust faulting is uncertain. It clearly post-dates the Chapin Wash sediments and their late movement on the surface. It may be contemporaneous with gentle folding along of the lower part of unit Tbs along NW-trending axes of the lower part of unit Tbs in the lower reaches of the Santa Maria River. If so, thrusting is also bracketed by 13 m.y. (the age of basal Tbs basalt flows) and 9 m.y. (the age of little-deformed basalts in the upper part of Tbs).

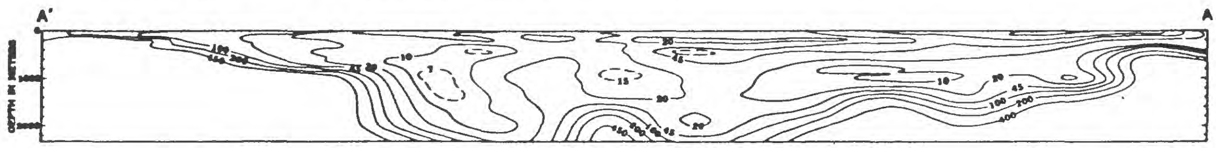

Figure 3.-- Schlumberger resisistivity profile along *A-A'*. Basment about 100 ohm-meters.

These structures record a long period of NE-SW crustal extension in the Date Creek basin area. This crustal extension began with early listric normal faulting and movement on the regional surface and continued with ongoing normal faulting and northeast-trending arching. The northeast-trending arches are viewed as longitudinal folds like those formed when a thick sheet of elastic material is stretched. The southwesterly directed thrust faulting is viewed as a compressional relaxation response after crustal extension ceased. The end of crustal extension and the period of compressionl relaxation occurred between 13 and 9 m.y. ago. Western Arizona has been largely structurally stable since that time. Note finally, that available data leaves open the question of how far crustal extension by listric normal faulting and detachment faulting extends to the northeast where extensive exposures of Precambrian rocks makes identification of faults difficult and a lack of a Tertiary rock record precludes dating of structural events. Without a pre-normal faulting Tertiary rock record one fault looks like another in the Precambrian.

REFERENCES

Gassaway, J. S., 1977, A reconnaissance study of Cenozoic geology in west-central Arizona (Master's thesis): San Diego, San Diego State University, 117 p.

Shackelford, T. J., 1975, Structural geology of the Rawhide Mountains, Mohave County, Arizona (Ph.D thesis): Los Angeles, University of Southern California, 175 p.

Shackelford, T. J., 1980, Tertiary tectonic denudation of a Mesozoic-early Tertiary(?) gneiss complex, Rawhide Mountains, western Aizona: Geology, v. 8, no. 4, p. 190-194.

LOWER AND MIDDLE PALEOZOIC EUGEOSYNCLINAL ROCKS IN THE EL PASO MOUNTAINS, NORTHWESTERN MOJAVE DESERT, CALIFORNIA

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An isoclinally folded and tectonically shuffled, pseudohomoclinal assemblage of lower and middle Paleozoic eugeosynclinal rocks 3200 m in tectonic thickness crops out between Mesquite and Iron Canyons in the central El Paso Mountains (Poole and Christiansen, 1980). It consists of chert, argillite, siltite, and subordinate greenstone, quartzite, conglomerate, and silty to sandy carbonate rock. The assemblage includes units designated 1-9 of the Garlock Formation by Dibblee (1952, 1967). Dibblee's unit 1 is underlain by his Mesquite Schist, which we regard as of possible Ordovician age, and his unit 9 is onlapped unconformably by his unit 10 of probable Carboniferous age.

Conodonts from sandy limestone of Dibblee's unit 5 are Middle to Late Devonian in age (A.G. Harris, written commun., 1975). Conodonts from separate beds in his unit 7 indicate that it is partly Late Devonian and partly Middle and Late Ordovician. Late Devonian conodonts occur in the structurally lowest part of Dibblee's unit 9; Early and Middle Ordovician graptolites, phyllocarids, orbiculoids, sponges, conodonts, and radiolarians occur throughout most of his unit 9. Most of unit 9 is Early and Middle Ordovician in age based on graptolite faunas studied by Ross. The beds that contain Ordovician graptolites are equivalent to zones 3-11 of the British stratotype, but the zones are disordered and, locally, are structurally interleaved with Upper Devonian rocks. Dibblee's unit 9 contains numerous isoclinal folds and imbricate thrust faults subparallel to beds resulting in a tectonic thickness of 1320 m. Lower Ordovician rocks, represented by graptolite zones 3-5, form the cores of anticlines and upper Middle Ordovician rocks, represented by zones 10-11, form the cores of synclines. It seems likely that internal deformation and thickening also has occurred in other, less fossiliferous, units in the El Paso Mountains assemblage. Because isoclinal folds and thrust faults repeat beds throughout Dibblee's units 1-9, the present thickness of the assemblage greatly exceeds the original depositional thickness.

Most of the Ordovician and Devonian rocks in units 1-9 of the El Paso Mountains assemblage resemble the Ordovician Vinini Formation and Devonian Slaven Chert in central Nevada and unnamed Devonian sandy limestone of Stewart (1979) at Miller Mountain in southwestern Nevada. In the El Paso Mountains, the pre-Carboniferous rocks may be part of the Roberts Mountains allochthon. If so, the allochthon extends farther to the southeast in southern California than simple projection of the outcrop belt of such rocks in Nevada would suggest. Either the orogenic belt was sinuous or the rocks may have been offset as much as 200 km in early Mesozoic time along a northwest-trending, left-lateral fault zone located between the El Paso Mountains and outcrops of similar rocks in Nevada.

REFERENCES

Dibblee, T. W., Jr., 1952, Geology of the Saltdale quadrangle, California: California Div. Mines Bull. 160, p. 7-43.

——— 1967, Areal geology of the western Mojave Desert, California: U.S. Geological Survey Prof. Paper 522, 153 p.

Poole, F. G., and Christiansen, R. L., 1980, Allochthonous lower and middle Paleozoic eugeosynclinal rocks in El Paso Mountains, northwestern Mojave Desert, California: Geol. Soc. America Abstracts with Programs for 1980, v. 12, no. 3, p. 147.

Stewart, J. H., 1979, Geologic map of Miller Mountain and Columbus quadrangles, Mineral and Esmeralda Counties, Nevada: U.S. Geological Survey Open-File Report 79-1145, 23 p.

GEOLOGY OF THE CRYSTALLINE BASEMENT COMPLEX, EASTERN TRANSVERSE RANGES, SOUTHERN CALIFORNIA: CONSTRAINTS ON REGIONAL TECTONIC INTERPRETATION

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About 3000 km^2 within the crystalline basement complex of the Eastern Transverse Ranges in the Chuckwalla, Orocopia, Eagle, Cottonwood, Hexie, Little San Bernardino, and Pinto Mountains of Riverside County, California were mapped at scales of 1:36,000 and 1:62,500 and compiled at 1:125,000 Pre-Jurassic(?) (i.e., older than the Mesozoic batholiths) rocks of the crystalline complex comprise two lithologically distinct terranes. These terranes are here called the Joshua Tree and San Gabriel terranes for regions of southern California in which their lithologies were initially characterized. The two terranes are superposed along a previously unrecognized low-angle fault system of regional extent, the Red Cloud thrust.

The structurally lower Joshua Tree terrane is defined as a stratigraphically coherent group of crystalline rocks that consists of Precambrian granite capped by a paleo-weathered zone and overlain nonconformably by orthoquartzite that interfingers westward with pelitic and feldspathic granofelses (Pinto gneiss). The quartzite contains near-basal quartz/quartzite clast conglomerates, and has well-preserved cross-bedding that appears upright wherever it has been observed. Pelitic and feldspathic granofelses crop out to the west of the quartzite exposures in four lithologically different belts that trend northnorthwest throughout the area mapped. These lithologic belts are interpreted to have been derived from stratigraphically interfingering sedimentary protoliths deposited in a basin offshore from a quartzose beach-sand protolith. In proximity to the early Red Cloud thrust, this whole stratigraphic package was pervasively deformed to granite gneiss, stretched pebble conglomerate, lineated quartzite, and schist.

A northeast-trending pattern of metamorphic isograds was orthogonally superimposed on the northnorthwest-trending protoliths of the Pinto gneiss. A central andalusite zone, located in the southern Little San Bernardino and Hexie, and northern Eagle Mountains, is flanked to the northwest and southeast by sillimanite zones. Coincident with this symmetrical distribution of aluminosilicates is an asymmetrical distribution of other pelitic mineral zones, with prograde cordierite-aluminosilicate-biotite- and K-feldspar-aluminosilicate-bearing assemblages to the northwest in the northern Little San Bernardino and Pinto Mountains, staurolite-bearing assemblages in a narrow zone in the southern Little San Bernardino-Hexie and northern Eagle Mountains, and retrograde chlorite-muscovite-bearing assemblages in the southernmost Little San Bernardino, Cottonwood, southern Eagle, Orocopia, and Chuckwalla Mountains. One occurrence of chloritoid-sillimanite in the central Eagle Mountains is apparently also retrograde. The crossing isograds are interpreted to result from a temporal increase in P_{H2O} relative to P_t from south to north through the field area. Comparison of the pelitic assemblages with experimental studies suggests peak conditions of $P_t \approx 3.5$ to 4 kb, T ≈ 525 to 625°C. The early prograde metamorphism pre-dated the thrusting event; the retrograde stage may have overlapped in time with the emplacement of the San Gabriel terrane allochthon. Cordierite-orthoamphibole-bearing assem-

blages are present in one stratigraphic zone of the Pinto gneiss.

The lithologies of the Precambrian San Gabriel terrane are viewed as layers in a three-part deep crustal section, with uppermost amphibolite grade pelitic (Hexie) gneiss intruded by granodioritic (Soledad) augen gneiss at the highest level, retrograded granulite (Augustine) gneiss at an intermediate level, and syenite-mangerite-jotunite at the lowest level exposed in the Eastern Transverse Ranges. The Hexie gneiss, characterized by sillimanite-garnet-biotite-bearing assemblages, is thrust over andalusite-bearing granofels of the Pinto gneiss.

The Red Cloud thrust system is inferred to have developed in three or four sequential structural events: 1) early thrusting that probably moved parallel to the ENE mineral lineations recorded in both plates; 2) regional folding of the initial thrust surface around NNE-trending axes; 3) later thrusting that broke with some component of westward movement across a fold in the older thrust surface to produce a stacking of crystalline thrust plates of the two terranes; 4) continued or renewed folding of both thrust faults with eventual overturning toward the SW. It is consistent with all observations to date to link these structural events into a single regional tectonic episode that resulted in allochthonous emplacement of the San Gabriel terrane westward over Joshua Tree terrane. The time of thrusting can only be loosely bracketed between 1195 m.y. and 165 m.y. ago.

The pre-batholithic terranes and the westward-vergent Red Cloud thrust are considered to be exotic with respect to pre-batholithic rocks and structures exposed to the north and east of the field area. The bounding discontinuity, which has been obliterated by intrusion of Mesozoic batholithic rocks, may represent a segment of an intracontinental transcurrent fault such as that proposed by Silver and Anderson (1974).

The Mesozoic plutonic rocks comprise two batholithic suites, both of which intrude the Joshua Tree and San Gabriel terranes and the Red Cloud thrust system. NW-SE trending belts of plutonic lithologies have been mapped within each suite: the oldest lithology of the younger suite intrudes the youngest lithology of the older suite. The older suite, Jurassic(?), lying to the NE, appears to have an alkalic character; the younger suite, Cretaceous(?), appears calc-alkaline. The older suite consists of biotite- and K-feldspar-bearing gabbro-diorites intruded by low-quartz monzogranites. The younger suite includes hornblende-biotite-sphene granodiorite intruded by porphyritic monzogranites, intruded in turn by non-porphyritic monzogranite.

The Eastern Transverse Ranges south of the Pinto Mountain fault are defined by several Cenozoic E-W left-lateral strike-slip faults that have a cumulative westward displacement from S to N of about 50 km. The left-lateral faults are interpreted to form part of a conjugate fault set with complementary right-lateral faults in the Mojave and Colorado Deserts. Stepwise restoration of documented displacements along the left-lateral faults and additional left-lateral bending of lithologic belts across the Pinto Mountain fault, and of approximated displacements along the right-lateral faults, aligns the pre-batholithic discontinuity discussed above with the path of the Mojave-Sonora megashear proposed by Silver and Anderson (1974). Paleozoic and Mesozoic rocks that are lithologically correlative with Great Basin and Colorado Plateau strata (Stewart and Poole, 1975;

Miller, 1977; Miller and Carr, 1978; Cameron et al., 1979; Stone and Howard, 1979; Cameron, 1980) all lie continentward of the restored discontinuity; the exotic terranes proposed by Silver (1971) and in this study all lie outboard of the restored discontinuity. In addition, all of the proposed enigmatic terranes of the western Mojave Desert (McCulloh, 1954; Miller et al., 1979; Burchfiel et al., 1980) lie outboard of the discontinuity.

Along the western boundary of the Eastern Transverse Ranges in the Little San Bernardino Mountains, the crystalline rocks have been pervasively cataclasized by an event that post-dates intrusion of the Cretaceous(?) plutonic rocks. The cataclasis is attributed to the Vincent-Orocopia-Chocolate Mountain thrust that is thought to superpose the diverse pre-batholithic and batholithic rocks of the Eastern Transverse Ranges above Pelona-type schist. The cataclastic foliation is folded along the length of the Little San Bernardino Mountains in an antiform that is inferred to be cored with Pelona-type schist. This fold may have formed a single antiformal feature comprising all the crystalline-rock antiforms now recognized along the San Andreas fault that are cored by Pelona-type schist. Displacements of the piercing points formed by the antiformal axis suggest 220 km of right-lateral offset on the present San Andreas strand and about 80 km of right-lateral offset along a fragmented older San Andreas strand that consisted of the San Francisquito, Fenner, and Clemens Well faults and a buried extension of this fault beneath the alluvial fill of the valley between the Chocolate and Chuckwalla Mountains.

REFERENCES

Burchfiel, B. C., Cameron, C. S., Guth, P. L., Spencer, J. E., Carr, M. D., Miller, E. L., McCulloh, T. H., 1980, Geol. Soc. Am., Abs. with Prog., v. 12, n. 7, p. 395.

Cameron, C. S., 1980, Geol. Soc. Am., Abs. with Prog., v. 12, n. 3, p. 100.

Cameron, S., Guth, P. L., and Burchfiel, B. C., 1979, Geol. Soc. Am., Abs. with Prog., v. 11, n. 7, p. 397.

McCulloh, T. H., 1954, in Jahns, R. H., ed., Geology of southern California: Calif. Div. Mines, Bull. 170, ch. 7, p. 13-24.

Miller, E. L., 1977, Geol. Soc. Am., Abs. with Prog., v. 9, n. 4, p. 467.

Miller, E. L., Burchfiel, B. C., and Carr, M. D., 1979, Geol. Soc. Am., Abs. with Prog., v. 11, n. 3, p. 92.

Miller, E. L. and Carr, M. D., 1978, in Howell, D. G. and McDougall, K. A., eds., Mesozoic paleogeography of the western United States: Pacific Sect., Soc. Econ. Paleon. Miner., Pacific Coast Paleogeography Symposium 2, p. 283-290.

Silver, L. T., 1971, Geol. Soc. Am., Abs. with Prog., v. 3, n. 2, p. 193-194.

Silver, L. T. and Anderson, T. H., 1974, Geol. Soc. Am., Abs. with Prog., v. 6, n. 7, p. 955-956.

Stewart, J. H. and Poole, F. G., 1975, Geol. Soc. Am. Bull., v. 86, p. 205-212.

Stone, P. and Howard, K. A., 1979, Geol. Soc. Am., Abs. with Prog., v. 11, n. 3, p. 130.

PRINCIPAL TECTONIC EFFECTS OF THE MID-TERTIARY OROGENY IN THE SONORAN DESERT PROVINCE

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From approximately 30 to 16 m.y. B.P., the Sonoran province of western Arizona experienced intense magmatism combined with unparalleled horizonal distension of the upper crust. Volcanic rocks, many of which had been mapped as Laramide or Cretaceous in age, abound in the province, and are rich in pyroclastic deposits. Compositionally, these volcanics range from andesitic basalt to high silica rhyolite. Potash-rich endmembers (i.e. ultrapottasic and/or peralkaline) appear anomalously common and precious metal mineralization often relates to silicic intrusive phases. Increasingly, holocrystalline plutonic rocks of mid-to late-Tertiary age are being recognized which petrologically, chemically and isotopically ($^{87}Sr/^{86}Sr$) cannot be distinguished from intermediate Laramide intrusive rocks. In fact, copper mineralization (so far, noncommercial) is commonly associated with the mid-Tertiary plutons.

Except for the mid-Tertiary trend toward higher potash and silica contents, there is considerable overlap of major element chemistries between mid-Tertiary and Laramide magmatic rocks. Both are largely calc-alkaline. Average initial strontium ratios of both groups fall without distinction into the range 0.7075 to 0.7085.

Structurally, an important aspect of the mid-Tertiary Orogeny is tilting and extension on low-angle, listric normal faults which strike NNW to WNW. The degree of this deformation varies considerably across the province with more severely tilted rocks (up to vertical) commonly occurring in discrete domains between less deformed areas. The direction of tilt is constant over large areas incorporating multiple mountain ranges. In northwestern Arizona these uniformly tilted domains define a regional antiform with northwest trend (Figure 1). Listric normal faulting ceased as the dominant structural process between about 16 and 13 m.y. B.P.

The recently recognized metamorphic core complexes, particularly their once subhorizontal, now arched zones of mylonitization constitute a fundamental tectonic element in the Oligocene-Miocene history of this and adjacent provinces. Deformed rock fabrics in the mylonites indicate extreme flattening and northeast extension of rock mass. This direction is more than fortuitously found to be nearly colinear with the axis of more brittle extension associated with mid-Tertiary dike emplacement and listric normal faulting.

A working model is therefore proposed which would link the mid-late Tertiary processes of intrusion, mylonitization and listric faulting (Figure 2). Dilational crustal spreading and dike-pluton emplacement occur in deeper levels; listric faults accomodate the spreading in cooler, brittle surficial levels, and mylonites develop, perhaps catalyzed by focused heat from sill-like intrusive centers, in zones of penetrative flattening or differential shear between dilational and brittle levels.

Northeast extension within core complexes outpaces that in neighboring terrains thereby creating transform-like discontinuities between the two regimes. Such features are postulated in the Wickenburg and Lake Mead regions where they bound a broad, northwest-elongate area of nearly continuous metamorphic complexes and pervasive southwest tilting (Figure 1).

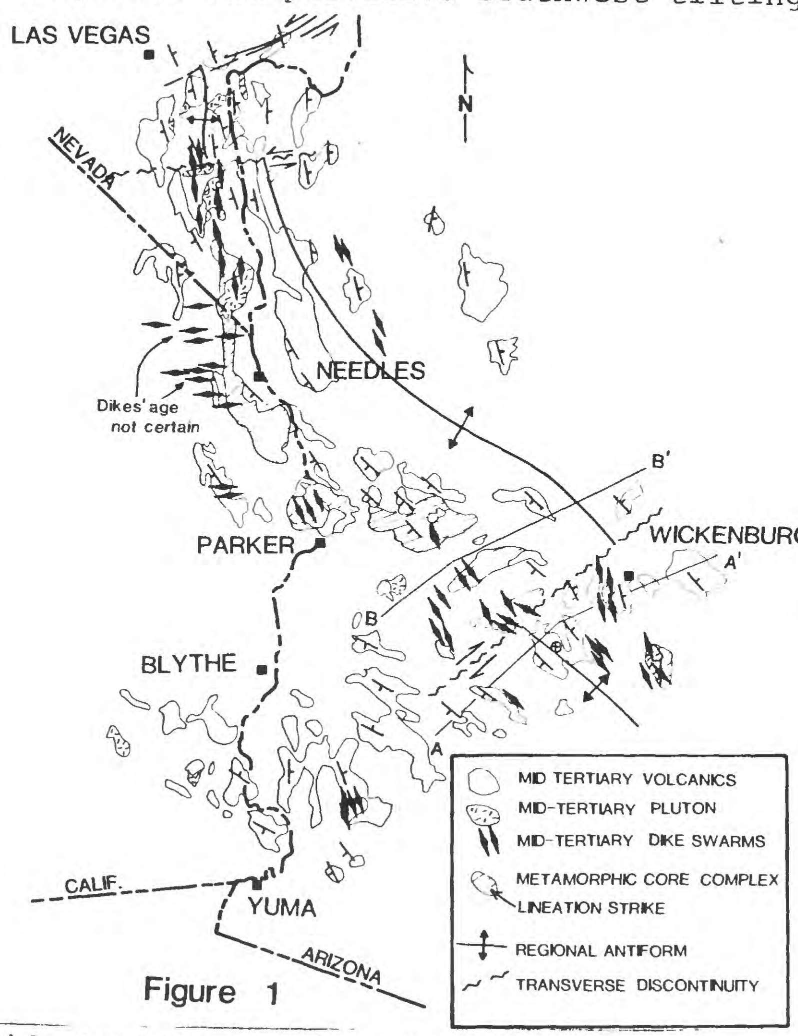

Figure 1 - Mid- to late-Tertiary tectonic features of the Sonoran desert province. Sections AA' and BB' shown on Figure 2.

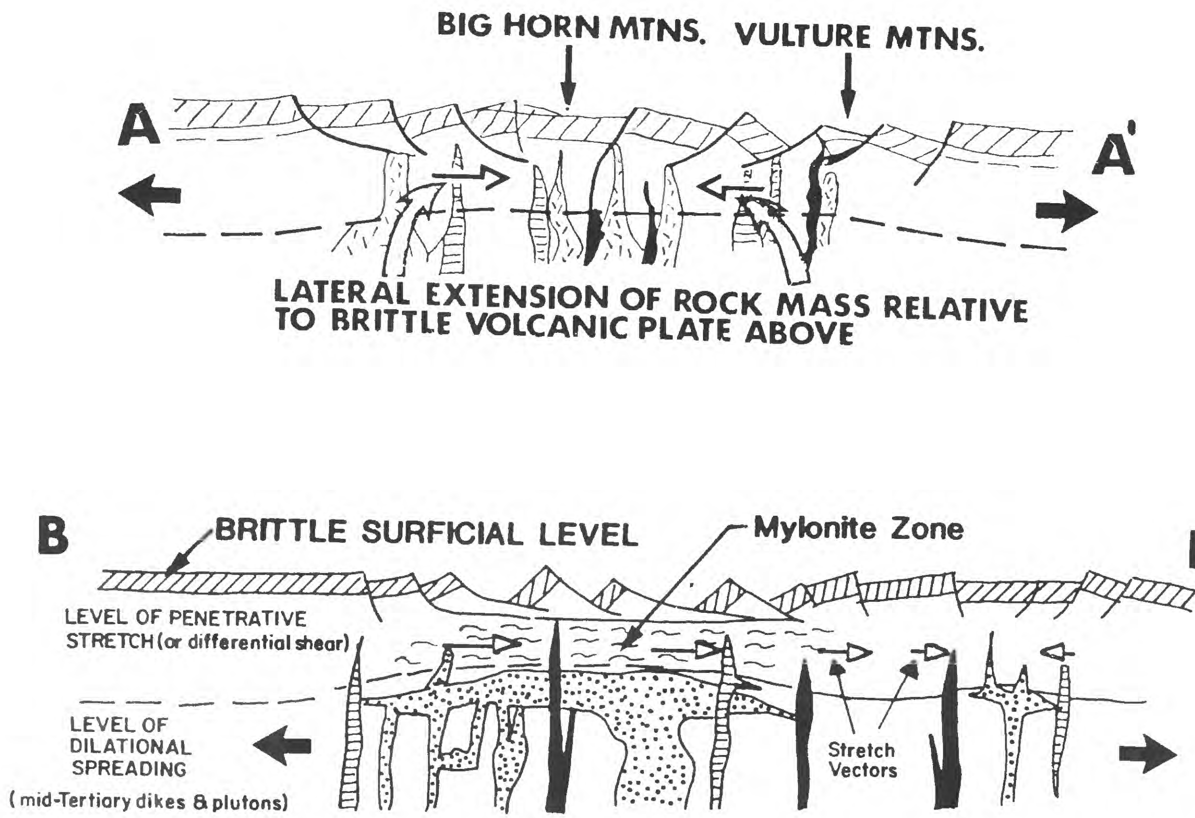

Figure 2 - Schematic cross sections illustrating working model for crustal extension and rotational fault tectonics in areas of regional tilted antiform (section AA') and metamorphic core complex (section BB'). Section lines are shown on Figure 1.

A HYPOTHESIS TO EXPLAIN ANOMALOUS STRUCTURES IN THE WESTERN BASIN AND RANGE PROVINCE

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Wright (1976) identified two deformational fields within the Basin and Range Province. Field I encompasses most of Nevada and is characterized by steeply dipping normal faults oriented NNE. Field II is bound approximately on the east by the Walker Lane and bound on the west by the Sierra Nevada block. Field II contains gently dipping normal faults oriented NS, and abundant conjugate-shears. Wright (1976) noted that deformational Field II is topographically and structurally distinct from the rest of the Great Basin because most of the mountain ranges trend northwestward. Slemmons (1967) noted that Walker Lane, a zone 10-20 miles wide and 450 miles in length, separates NW-SE topographic trends to the west from N-S to NNE-SSE trends to the east.

Troxel and others (1972) suggested that the land north of the Garlock fault had been stretched. Davis and Burchfiel (1973) conclude that the Garlock fault was a transform structure; that the southern Basin and Range Province is spreading faster than its northern counterpart and that the Basin and Range Province is still being formed by EW extension without significant right shear. This model, however, does not totally explain the structural anomaly found in the western Basin and Range Province. New data allows us to build upon the hypothesis of Davis and Burchfiel to explain the anomalous structure found in the western Basin and Range Province. A discussion of possible mechanism follows.

Zoback and Zoback (1980) report that the Sierra Nevada Block has a least principal horizontal stress direction oriented WNW to NW and is a region of stress transition from strike slip deformation on the San Andreas to extensional deformation in the Basin and Range Province. Zoback and Zoback (1980) also state that the least principal horizontal stress direction for the Basin and Range is WNW and is a region of active crustal spreading by distributed normal and oblique slip normal faulting. However, the westernmost part of the province exhibits both purely strike-slip and purely normal faulting (Slemmons and others (1979)).

My observations indicate that the structure of the Coso Range in the western Basin and Range Province is in transition between the San Andreas and Basin and Range Province, based on (1) a nearly EW orientation in the least principal horizontal stress direction, and (2) abundant NW oriented right-slip faults. This is probably the case for the rest of the transition area between the Walker Lane and the Sierra Nevada from about Mono Lake to the Garlock fault (Carr, 1974; Wright, 1976). If this observation holds true then the following hypothesis might be considered.

Figure 1 is a fault map modified from Atwater (1970). If the Walker Lane (WL) were a conjugate-shear to the deep seated compressional forces

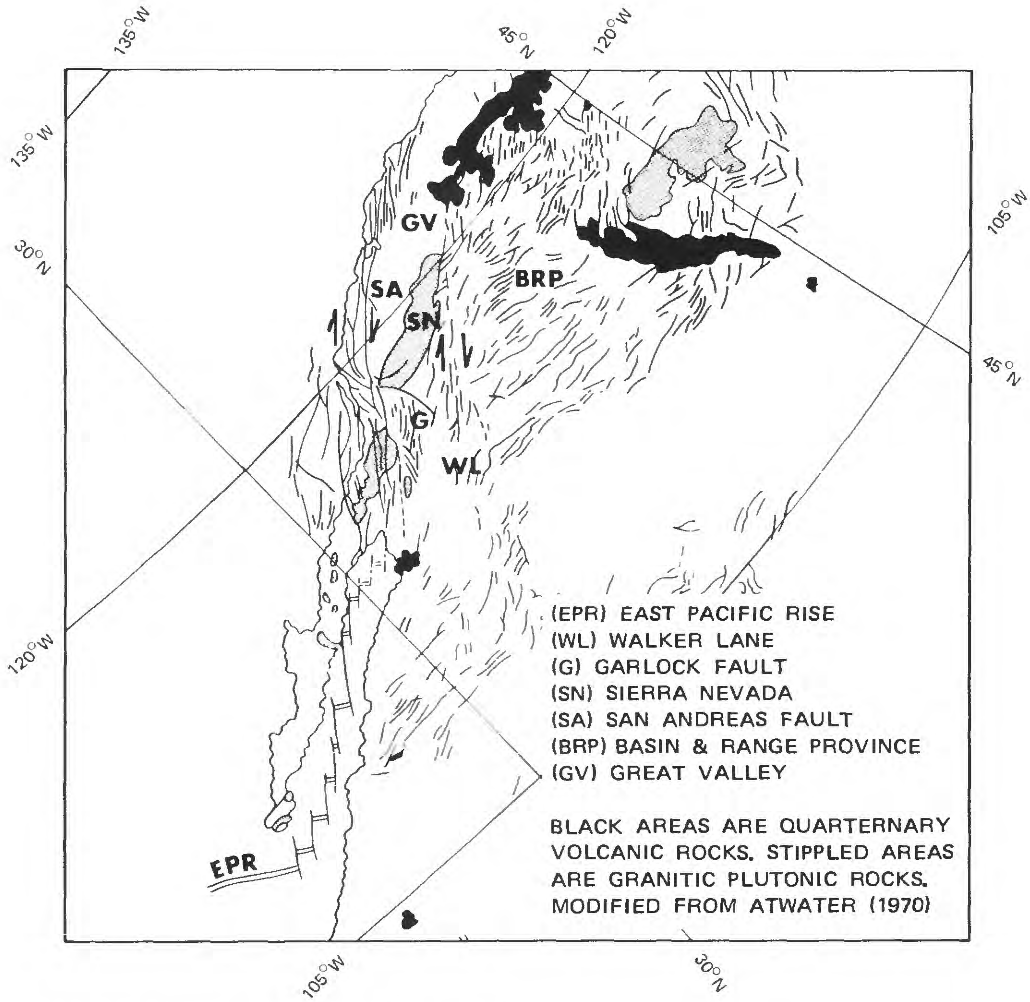

FIGURE 1. Fault Map of the Western United States and Mexico.

extending the Basin and Range Province (BRP) then the Sierra Nevada Block (SN) would migrate northwestward along the Walker Lane failure plane. If the San Andreas fault increased its slip rate or had a higher rate of slip, then a drag-rotation (clockwise) of the Sierra Nevada might be expected to occur. This rotation would explain (1) the bend in southern end of the Kern Canyon fault, (2) the existence of the Garlock fault, and (3) the structural anomaly between the Walker Lane and the Sierra Nevada Block.

REFERENCES

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geol. Soc. Amer., Bull., v. 81, p. 3513-3536.

Carr, W. G., 1974, Summary of tectonic and structural evidence for stress orientations at the Nevada Test Site: U.S. Geological Survey Open-File Report 74-176, 53 p.

Davis, G. A. and Burchfiel, D. C., 1973, Garlock fault: An intracontinental transform structure, southern California: Geological Society of America Bulletin, v. 84, p. 1407-1422.

Roquemore, G. R., 1978, Evidence for Basin and Range/Sierra Nevada transitional zone structures in the Coso Mountains, California: Geological Society of America Abstracts with Programs, v. 10, p. 144.

Slemmons, D. B., 1967, Pliocene and Quaternary crustal movements at the Basin-and-Range Province, USA, J. Geosci., 10, 91-101.

Slemmons, D. B., Van Wormer, D., Bell, E. J., and Silberman, M. L., 1979, Recent crustal movements in the Sierra Nevada-Walker Lane region of California-Nevada: Part I, Rate and Deformation. In: C. A. Whitten, R. Green, and B. K. Meade (eds.), Recent Crustal Movements, 1977: Tectonophysics, v. 52, p. 561-570.

Troxel, B. W., Wright, L. A., and Jahns, R. H., 1972, Evidence for differential displacements along the Garlock fault zone, California: Geol. Soc. America Abs. with Programs, v. 4, p. 250.

Wright, L. A., 1976, Late Cenozoic fault patterns and stress fields in the Great Basin and westward displacement of the Sierra Nevada block: Geology, v. 4, p. 489-494.

Zoback, M., Thompson, G. A., 1978, Basin and Range rifting in northern Nevada: Clues from a mid-Miocene rift and its subsequent offsets: Geology, v. 6, p. 111-116.

NEWLY DISCOVERED SLIVER OF RAND (?) SCHIST WITHIN THE SAN EMIGDIO MOUNTAINS (SOUTHERNMOST SIERRA NEVADA TAIL), CALIFORNIA

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Within the west-trending tail of the southernmost Sierra Nevada (San Emigdio mountains) a distinctive belt of schist and quartzite has been mapped between Grapevine and San Emigdio Canyons (figure 1) that is of lower metamorphic grade than the surrounding rocks, and is separated from the surrounding terrane by faults wherever the contact relations have been observed.

The schist and quartzite belt is characterized by coarse, dark biotite-rich layers alternating with impure quartzite layers, which are also quite dark colored. In thin section the most striking feature of these rocks is the abundance of large "dirty," poikilitic masses of virtually untwined sodic plagioclase strongly dusted with graphite or other carbonaceous matter. Gray chlorite crystals are also present (in addition to penninitic biotite alteration products) that appear to be "primary" and another indicator of the relatively low metamorphic grade of this belt. Also distinctive in the schist and quartzite belt are prominent, thick white "bull quartz" veins or sills. The physical appearance and metamorphic grade of these rocks is strikingly reminiscent of rocks I have examined in the Rand Schist in the western part of the Rand Mountains and also to some of the rocks in the Rand Schist slivers along the Garlock fault between the San Andreas fault and the Rand Mountains. I therefore suggest that the schist and quartzite belt in the San Emigdio Mountains is a correlative of the Rand Schist, which has long been considered to be related to the Pelona-Orocopia Schist terrane. The general setting and shape of the probable Rand Schist in the Sierra Nevada tail suggests it is a sliver along a transcurrent fault, but at its east end the north contact of the schist and quartzite appears to plunge under the adjacent dark amphibolitic gneiss unit. The south contact appears to be an abrupt, steeply dipping fault contact against granodiorite and metasedimentary rocks of strikingly different character from the schist and quartzite belt. The faulted belt does appear to be pierced by a felsic granitic rock whose age is presently unknown.

It is probably no mere coincidence that the faulted south contact of the Rand Schist sliver in the San Emigdio Mountains essentially lines up with the Pastoria fault zone of Crowell (1952). I suggest that both these features are part of a fundamental break in the basement rocks of the Sierran tail. West from the Garlock fault on a somewhat crinkled but generally east-west trend to the end of the basement outcrop at the west end of the San Emigdio Mountains metasedimentary rocks of continental affinity and associated granodiorite on the south are in abrupt contact with hornblende-rich plutonic and metamorphic rocks of possible oceanic affinity on the north.

The complete difference of rock types across this "break" for a strike length of nearly 50 km along the Sierran tail suggests to me a transcurrent fault that has been crinkled and further distorted by pressure from the San Andreas fault. The Rand Schist sliver along this break is also compatible with transcurrent movement. Clearly the age and precise delineation of the felsic granitic that seems to cut the "break" is critical and deserving of further detailed work. Could this structural break be an older strand of the Garlock fault?

I would be remiss if I did not acknowledge here the "mental push" I was given by Thomas Davis (U.C. Santa Barbara, now with ARCO Oil and Gas Company). His comments to me about finding "Pelona Schist" in place in the San Emigdio Mountain near San Emigdio Canyon finally crystallized my suspicions that the dark schist and quartzite belt I had long been agonizing over, could in no way be part of the amphibolitic gneiss unit, and was indeed most probably a structurally displaced sliver of Rand Schist.

REFERENCES

Crowell, J. C., 1952, Geology of the Lebec quadrangle, California: Calif. Div. Mines Special Report 24, 23 p.

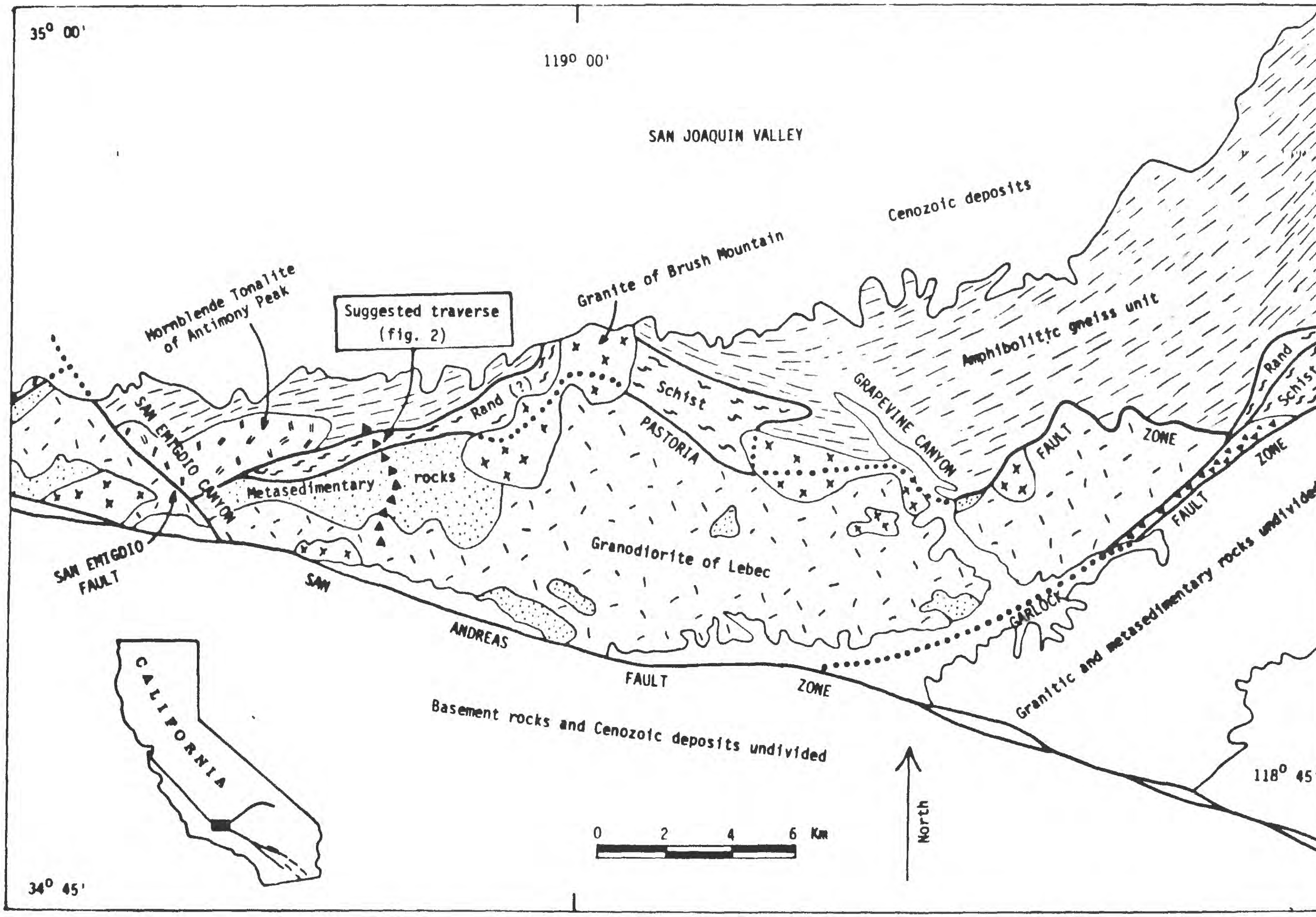
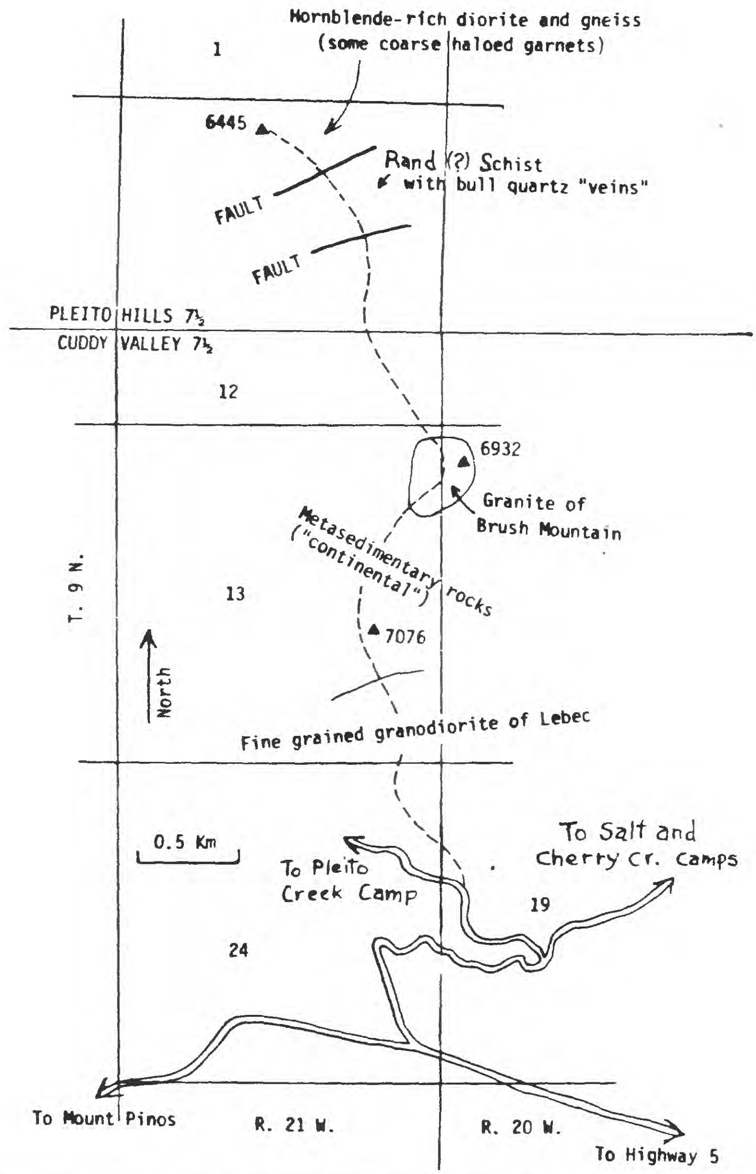


Figure 1. Generalized geologic map of the Sierra Nevada tail showing the probable Rand Schist sliver in the San Emigdio Mountains, California



One of the best places to see the Rand Schist belt and the adjacent rock types is along a ridge east of Pleito Creek. Take the Frazier Park turnoff west from U.S. Highway 5 between Gorman and Lebec. About 12 miles (19 km) on the road to Mount Pinos a Forest Service Road turns off to the north (right) to Pleito, Salt, and Cherry Creek Camps. At the junction (about 1 mile), continue toward Pleito Creek (left) for about 0.3 mi to a "parking lot" on the right. From there you hike north along an old road (no cars now, please). The road dies out before you get to the Rand Schist belt, but with the Pleito Hills and Cuddy Valley 7-1/2 minute quadrangle maps you cannot miss it. The faults are not exposed, but sheared rocks in the saddles leave little doubt as to the relations. The condition of the road to the "parking lot" varies considerably with time; if you do not have a 4-wheel drive vehicle, you may want to park near the road to Mount Pinos and add a couple of kilometers to your walking traverse.

Figure 2. Directions to and location of traverse to examine probable Rand Schist sliver in the San Emigdio Mountains, California

QUALITATIVE ANALYSIS OF AIRBORNE GAMMA-RAY GEOPHYSICAL DATA IN THE CALIFORNIA DESERT

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Analysis of airborne gamma-ray spectrometer data began in March 1979, and ceased in January 1980. Data were obtained from NURE and BLM contractors. NURE coverage was nearly desertwide, excluding only the Santa Ana, San Diego, Los Angeles, and San Bernardino 1^o x 2^o sheets. BLM contracts covered ten selected areas, plus the East Mojave Planning Unit. Data were obtained in the form of standard deviation maps, geophysical profiles, and maps showing contours in equivalent ppm of uranium, thorium, and K^{40}. All three data formats were available for some areas; other areas had only one data form, or no coverage. Data analysis for equivalent uranium, equivalent thorium, and equivalent K^{40} anomalies was done for all covered areas. Data analysis for equivalent uranium/equivalent thorium ratio anomalies was done for all covered areas except the Death Valley 1^o x 2^o sheet.

Results consist of delineated areas interpreted to have anomalously high gamma radiation in the selected ranges of intensity associated with uranium, thorium, and K^{40}, plus uranium/thorium ratios. These areas are identified on flight lines, and interpolated between flight lines on the basis of lithology and relative anomaly strength. Results are consistent where the available data were in a consistent format. Where two different data formats abut or overlap, inconsistencies are occasionally found. The most inconsistencies are found where the Death Valley 1^o x 2^o sheet bounds other survey areas. Agreement was good elsewhere. Four anomalies were field checked in November 1979, using ground traverses. Field data have not been analyzed as of January 1981.

The delineated anomalies are shown on a desertwide acetate overlay map, and on overlay maps 10a, 10b, and 10c in the BLM California Desert District's Geology-Energy-Minerals Resource Area (GRA) files. All data are now housed in the BLM State Office in Sacramento, but are scheduled to be moved to Riverside in mid 1981.

OXYGEN ISOTOPE STUDY OF MESOZOIC BATHOLITHIC ROCKS IN SOUTHWESTERN CALIFORNIA AND SOUTHERN ARIZONA

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A $\delta^{18}O$ survey of Mesozoic batholithic rocks has been conducted in a corridor adjacent to, and extending ~100 km northeast from the San Andreas Fault zone between 35°N and 33°30'N. Mesozoic batholithic rocks in south-central and southwestern Arizona have also been sampled for $\delta^{18}O$. The California survey has revealed "fossil" meteoric-hydrothermal systems within the Triassic-Jurassic (?) Sidewinder Volcanic Series, Ord Mountain Group and associated plutons near Barstow, California. Plutons in the Chuckwalla, Cotton and Little San Bernardino mountains also exhibit meteoric-hydrothermal alteration of their $\delta^{18}O$ compositions. Rocks within the "fossil" systems have Δqtz-W.R. > +2.0‰, which indicates subsolidus interaction between hot meteoric water and rock. The most geologically interesting, and largest altered zone spans 800 km^2 from Barstow south to Lucerne Valley, and from Victorville east to the Rodman mountains. Cretaceous (?) and Permo-Triassic plutons within the area exhibit whole-rock $\delta^{18}O$ between +7.2‰ and 9.2‰ and have apparently not been markedly affected by meteoric-hydrothermal fluids. Values between -3.5‰ and +5.7‰ are characteristic within Triassic-Jurassic (?) intrusive complexes up to 10 km in diameter consisting of stocks and flows of andesite and latite intruding and intruded by granodiorite to monzogranite plutons. The most intensely ^{18}O - depleted rocks occur near elliptical "ring structures" marked by aplitic monzogranite and chloritized or sercitized volcanic rocks. These are the lowest-^{18}O meteoric-hydrothermal systems thus far found in the southwestern North American cordillera.

Primary whole-rock $\delta^{18}O$ of a large number of the Mesozoic granitic rocks in southeastern California and southern Arizona ranges from +7.2‰ to +10.9‰ with Δqtz-W.R. around +1.2‰; the latter represents "normal" fractionation of oxygen isotopes during crystallization of magma. $\delta^{18}O$ is bimodally distributed within the range of compositions with peaks near +8.0‰ and +9.3‰. Each population spans the limit of $\delta^{18}O$ variation that can be attributed to differention (± 0.5‰). Each peak, then, represents a suite of melts whose source region(s) had similar oxygen isotopic compositions. An interesting point is that the peraluminous melts which gave rise to the two mica ± garnet-bearing granitoids in the southwestern North America cordillera had $\delta^{18}O$ compositions which span the range of $\delta^{18}O$ for both "suites". The bulk of peraluminous granitoids, however, fall between +8.7‰ and +9.2‰. Since pelitic schists generally have $\delta^{18}O$ >> 15‰, simple mass balance dictates that such rocks may not play a dominant role as source material during generation of the peraluminous melts. Further work is in progress to determine the distribution of $\delta^{18}O$ with space and time parameters in the Mesozoic batholithic rocks of the southwestern United States.

EARLY AND MIDDLE PALEOZOIC MARGIN OF THE NORTH AMERICAN CONTINENT IN THE SOUTHWESTERN UNITED STATES AND NORTHERN MEXICO

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Two models of the early and middle Paleozoic continental margin of North American in the southwestern United States and northern Mexico have been proposed.

Model I. Mexico and Central America were part of the North American continent during the early and middle Paleozoic (fig. 1) and formed a relatively narrow southward extension of the North American continent (Guzman and deCerna, 1963; Palmer, 1974; Helwig, 1975; Scotese and others, 1979). This concept is based on the similarity in age and lithology of widely spaced outcrops of Precambrian and, Paleozoic(?) crystalline basement rocks in eastern Mexico and central America that suggest a continuity of basement terrains. By late Paleozoic time, continuity across this region is suggested by similar faunal provinces (C. A. Ross, 1979).

Model II. Most of Mexico and Central America were not part of the North American continent in early and middle Paleozoic time. Instead, the southern margin of the continent extended eastward across northern Mexico and joined the early and middle Paleozoic Ouachita margin in the south-central United States (fig. 1). This concept was described by Bridges (1964), although he later rejected the idea (Bridges, 1970); more recently the concept has been illustrated or described by R. J. Ross (1976, fig. 1), Stewart (1976), and Peiffer-Rangin (1979). The concept is based on an apparent eastward trend of Cordilleran geosynclinal rocks in Sonora, Mexico (Peiffer-Rangin, 1979) and the general online eastward trend of the Ouachita geosyncline of the south-central United States. The connection, if any, between these two approaching geosynclinal belts is obscured in a region of few outcrops in northern Mexico. Nevertheless, lower and middle Paleozoic shelf rocks that can be tied with assurrance to either the Cordilleran or Ouachita continental margins do not extend south of about latitude 28^{o} in Mexico. Even upper Paleozoic carbonate rocks that appear to be related to shallow-water deposition along the continental margin occur only north of this latitude; upper Paleozoic rocks to the south are more shaly, commonly contain volcanic or volcanoclastic units, and were deposited partly in a deeper water environment. Model II apparently requires that Mexico and Central America were assembled and attached to North America from the late Paleozoic to the Cenozoic from several microplates (Gose and others, 1980). Some of these microplates might have rifted from North or South America, or even Africa, in a manner similar to that proposed by Morris (1974).

Model II has important ramifications concerning the geologic evolution of the southwestern United States. The Mojave Desert region, if model II is correct, was at a "corner" of the continent, an area where changes in trend, style, and timing of tectonic events might be expected, where the first effects of plate collisions might be felt, and where strike-slip faults cutting across the exposed corner might be more likely to occur. Model II also allows speculation that some Mesozoic and early Cenozoic features, such as the east trend of Late Triassic volcanic-rich sediments across the southern United States (Stewart, 1969) or the possible eastward curve of the Cordilleran orogenic belt in California and Arizona (Drewes, 1978) are related in some way to position of the Paleozoic margin, perhaps even that the continental margin across northern

Mexico persisted into the early Mesozoic. These Mesozoic features mimic the shape, but are inland of the proposed Paleozoic margin.

Both models presented here permit or require complex Mesozoic or Cenozoic tectonic displacements (Anderson and Silver, 1974; Scotese and others, 1979; Gose and others, 1980) to account for the present distribution of Paleozoic rocks in Mexico and Central America. The models shown here (fig. 1) suggest that the Paleozoic history of this same region may have been equally complex due in large part to the assembly of what were two continents in the lower and middle Paleozoic (North American and Gondwana) into one continent in the upper Paleozoic (Pangaea). Such an assembly allows for a variety of plate tectonic interactions in the region where the two continents join.

References

Bridges, L. W., 1964, Regional speculations in northern Mexico, in Geology of Mina Plomosas-Placer de Guadalupe area, Chihuahua, Mexico: Field Trip Guidebook, West Texas Geological Society Publication 64-50, p. 93-98.

_____1970, Paleozoic history of the southern Chihuahua tectonic belt, in Seewald, Ken, and Sundeen, Dan, eds., The geologic framework of the Chihuahua tectonic belt: West Texas Geological Society, University of Texas at Austin, p. 67-74.

Drewes, Harald, 1978, The Cordilleran orogenic belt between Nevada and Chihuahua: Geological Society of America Bulletin, v. 89, p. 641-657.

Gose, W. A., Scott, G. R., and Swartz, D. K., 1980, The aggregation of Mesoamerica: Paleomagnetic evidence, in Pilger, R. H., Jr., ed., The origin of the Gulf of Mexico and the early opening of the central North Atlantic Ocean: School of Geosciences, Baton Rouge, Louisiana State University, p. 51-54.

Guzman, E. J., and deCerna, Zoltan, 1963, Tectonic history of Mexico, in Childs, O. E., and Beebe, B. W., eds., Backbone of the Americas, a symposium: American Association of Petroleum Geologists Memoir 2, p. 113-129.

Helwig, James, 1975, Tectonic evolution of the southern continental margin of North America from a Paleozoic perspective, in Nairn, A. E. M., and Stehli, F. G., eds., The ocean basins and margins. Vol. 3, The Gulf of Mexico and the Caribbean: New York and London, Plenum Press, p. 243-255.

Morris, R. C., 1974, Sedimentary and tectonic history of the Ouachita Mountains, in Dickinson, W. R., ed., Tectonics and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 120-142.

Palmer, A. P., 1974, Search for the Cambrian World: American Scientist, v. 62, p. 216-224.

Peiffer-Rangin, Francoise, 1979, Les zones isopiques du Paléozoïque inferieur du nord-ouest mexicain, té moins du relais les Appalaches el la cordillère ouest-américaine: C. R. Acad. Sc. Paris, v. 288, no. 20, Serie D, p. 1517-1519.

Ross, C. A., 1979, Late Paleozoic collision of North and South America: Geology, v. 7, p. 41-44.

Ross, R. J., 1976, Ordovician sedimentation in the western United States, in Bassett, M. G., ed., The Ordovician System: Proceedings of a Paleontological Association Symposium, Birmingham, Sept. 1974: University of Wales Press and National Museum of Wales, Cardiff, p. 73-105.

Scotese, C. R., Bambach, R. K., Barton, Colleen, Vander Voo, Rob, and Ziegler, A. M., 1979, Paleozoic base maps; Journal of Geology, v. 87, p. 217-277.

Silver, L. T., and Anderson, T. H., 1974, Possible left-lateral early to middle Mesozoic disruption of the southwestern North American craton margin [abs.]: Geological Society of America Abstracts with Programs, v. 6, p. 955.

Stewart, J. H., 1969, Major upper Triassic lithogenetic sequences in the Colorado Plateau region: American Association of Petroleum Geologists, v. 53, p. 1866-1879.

_____1976, Late Precambrian evolution of north America: Plate tectonics implications: Geology, v. 4, p. 11-15.

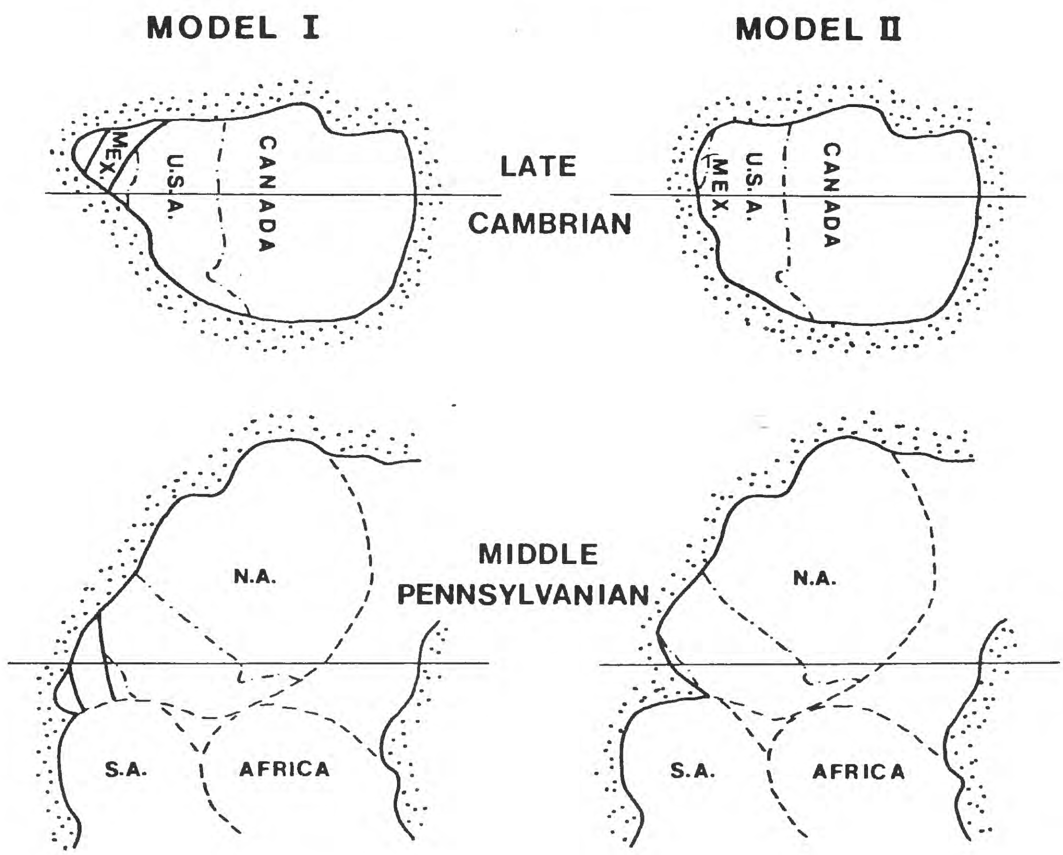

Figure 1. Late Cambrian and Middle Pennsylvanian reconstructions for models I and II. General paleogeography and positions of continents with respect to equator after Scotese and others (1979). Horizontal line is inferred equator for time indicated. Dot and dash pattern indicates international boundaries in North America. Dashed lines indicate limits of present day continents within Middle Pennsylvanian continent. Heavy lines in Mexico and the United States idicate major shear zones along which Mexico and Central America are rotated westward with respect to North America. Dotted pattern indicates miogeoclinal belts fringing the continents. Other models for the middle Pennsylvanian can be made using the "Pangaea B" reconstruction of Irving (1977) in which South America lies against the northeastern part of the United States.

PALEOZOIC METASEDIMENTARY ROCKS OF THE SOUTHEASTERN MOJAVE DESERT REGION, CALIFORNIA AND WESTERN ARIZONA

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Deformed, regionally metamorphosed Paleozoic strata occur as isolated outcrops throughout the southeastern Mojave Desert region of California and adjacent western Arizona (Figure 1). Paleozoic strata in the southeastern part of this region, including the Palen, Arica, Big Maria, Little Maria, Riverside, and Buckskin Mountains, are metamorphosed equivalents of the classic cratonal Paleozoic sequence of the western Grand Canyon, Arizona (Figure 2A). Farther northwest, in the Kilbeck and Fenner Hills and in the Old Woman, Piute, and Little Piute Mountains, metamorphosed Paleozoic strata are correlated with nonmetamorphosed Paleozoic sequences transitional between cratonal and miogeoclinal as exposed in the nearby Providence, Marble, and Ship Mountains (Figure 2B). Throughout the region, Precambrian crystalline rocks are commonly exposed unconformably beneath the metamorphosed Paleozoic sequence, and Mesozoic metasedimentary rocks commonly overlie it. Original lithologic features, fossils, and depositional thicknesses of the Paleozoic strata in the region generally have not been preserved because of metamorphism and severe ductile deformation. The strata are thus correlated solely on the basis of general lithology and stratigraphic sequence.

Paleozoic epicontinental strata once extended continuously from the southern Great Basin and Colorado Plateau provinces across the Mojave Desert region at least as far west and southwest as the Big Maria and Palen Mountains. Relict exposures of this sedimentary blanket and the underlying Precambrian continental basement in the southeastern Mojave Desert region define a terrane which has been disrupted by Mesozoic thrust faults and by Tertiary detachment faults but which otherwise appears to be structurally coherent. The Jurassic Mojave-Sonora megashear (Anderson and Silver, 1979), if this fault extends northwestward from the area where it has been mapped in Sonora, Mexico, into the Mojave Desert region, must pass somewhere southwest of the Paleozoic exposures in the Big Maria and Palen Mountains. Paleozoic epicontinental strata correlative with those of the southeastern Mojave Desert region occur 100 km to the west in the San Bernardino Mountains and in the Victorville area (Stewart and Poole, 1975; Miller, in press). Assuming that these western Paleozoic outcrops are autochthonous, Paleozoic paleogeographic trends which can be traced through the southeastern Mojave Desert apparently extend across the southwestern Mojave as well until finally terminating against the San Andreas Fault (Stewart and Poole, 1975). If this assumption is valid, it would appear improbable that any major fault passes between the southeastern and southwestern Mojave Desert regions, meaning that the Mojave-Sonora megashear would most likely pass south of the San Bernardino Mountains and come to an end against the San Andreas Fault.

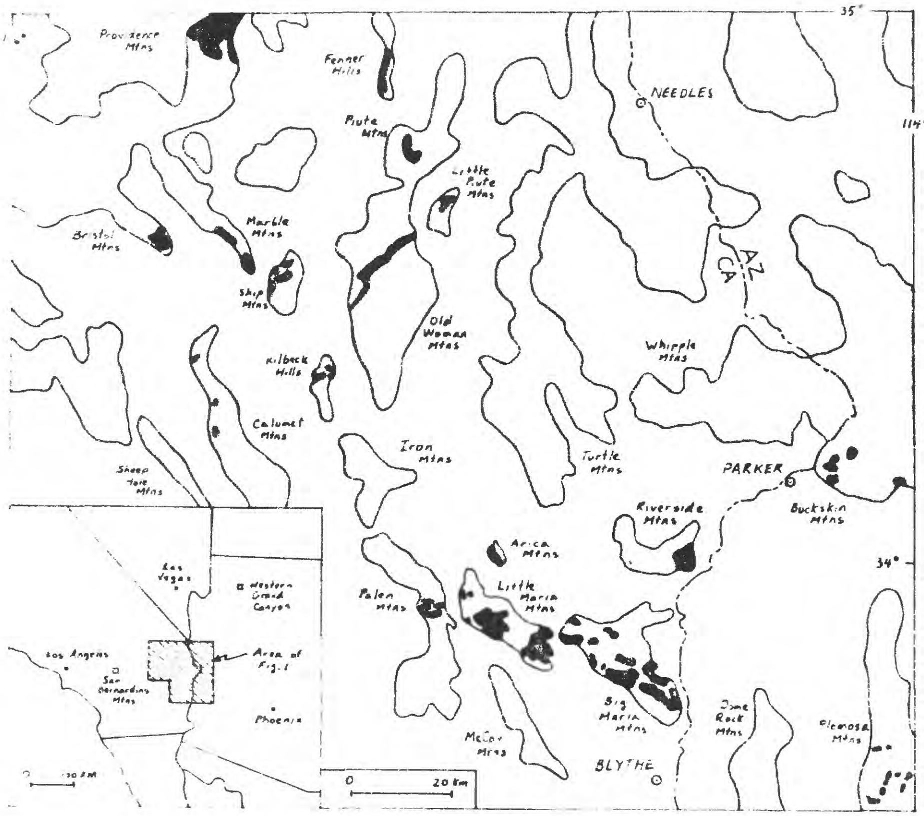

Figure 1. Map showing Paleozoic outcrop localities in the southeastern Mojave Desert region. Mountainous regions shaded; Paleozoic outcrops solid. The Paleozoic strata are metamorphosed and ductilely deformed at all localities except the Providence, Marble, and Ship Mountains.

REFERENCES

Anderson, T. H., and Silver, L. T., 1979, The role of the Mojave-Sonora megashear in the tectonic evolution of northern Sonora, in Anderson, T. H., and Roldan-Quintana, J., eds., Geology of Northern Sonora: Geological Society of America 1979 Annual Meeting Field Trip Guidebook no. 27, p. 59-68.

Miller, E. L., in press, Geology of the Victorville region, California: Geological Society of America Bulletin.

Stewart, J. H., and Poole, F. G., 1975, Extension of the Cordilleran miogeosynclinal belt to the San Andreas Fault, southern California: Geological Society of America Bulletin, v. 86, p. 205-212.

A

Lithology	Thickness	Correlation	Age
Schist, anhydritic schist, quartzite	0–100+ m	Uncertain (poss. in part Moenkopi)	Mesozoic
Calcite and dolomite marble, in part chert-banded; schistose at base	100–350 m	Kaibab Ls	Permian
Fine-grained vitreous quartzite	10–50 m	Coconino Ss	
Schist and calc-schist	10–30 m	Hermit Shale	
Massive and layered calc-silicate rock, calcareous quartzite, siliceous marble, and pure calcite marble	100–500 m	Supai Fm	?—— ? Penn-sylvanian
White calcite marble, in part chert-banded	5–50 m	Redwall Ls	Missis-sippian
Massive and layered dolomite marble	100–300 m	Temple Butte Ls – – ? – – – – ? – – Unnamed dolomite of western Grand Canyon	Devonian – ? – – ? – Cambrian
Banded calcite marble	5–30 m	Muav Ls	
Mica schist, thinly layered quartzite, and minor carbonates	5–50 m	Bright Angel Sh	
Arkosic quartzite, in part conglomeratic	10–20 m	Tapeats Ss	
Crystalline rocks, predominantly gneiss	—	Older Precambrian basement	

B

Lithology	Thickness	Correlation	Age
Schist	0–100+ m	Moenkopi Fm (?)	Mesozoic
Dolomite and calcite marble, in part chert-banded	30–50 m	Kaibab Ls	Permian
Fine-grained vitreous quartzite	30 m	Coconino Ss	
Schist and quartzite	30 m	Hermit Shale	
Calcite marble, mostly sandy; thick lenses of brown-weathering calc-areous quartzite and calc-silicate rock; minor fine-grained vitreous quartzite	150–200 m	Bird Spring Formation	?—— —? Penn-sylvanian
White calcite marble, in part chert-banded	30–50 m	Monte Cristo Ls	Missis-sippian
Massive and layered dolomite marble	100–300 m	Sultan Ls – ?– – – – – ?– Nopah Fm – ? – – – –? Bonanza King Fm (Banded Mountain Member)	Devonian ?– – – –? Cambrian
Banded calcite marble	10–20 m	Bonanza King Fm (Papoose Lake Mbr)	
Mica schist, thinly layered quartzite, and minor carbonates	10–30 m	Bright Angel Sh	
Massive orthoquartzite	2–10 m	Tapeats Ss	
Cross-bedded arkosic quartzite, in part conglomeratic	30–50 m		
Crystalline rocks, predominantly gneiss	—	Older Precambrian basement	

Figure 2. Generalized stratigraphic columns for Paleozoic metasedimentary rocks in the southeastern Mojave Desert region. A: Column for southeastern localities (Palen, Arica, Big Maria, Little Maria, Riverside, and Buckskin Mountains). B: Column for northwestern localities (Kilbeck and Fenner Hills; Old Woman, Piute, and Little Piute Mountains). Thicknesses are estimated structural thicknesses.

THE ORIGIN OF A MIOCENE BASALT-RHYOLITE SUITE, SOUTHERN BASIN AND RANGE PROVINCE, WESTERN ARIZONA

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Miocene volcanic rocks in the Castaneda Hills and northwestern part of the Artillery Peak 15' quadrangles, west-central Arizona, are interbedded with continental clastic sedimentary rocks, minor limestone, gravity glide blocks of Precambrian(?) and Paleozoic(?) rocks, and monolithologic mega-breccia. The units we have mapped correlate with the Artillery and Chapin Wash Formations of Lasky and Webber (1949). In particular, basalt in their Artillery Formation is equivalent to our older basalts. Their Cobwebb Basalt, basalt in the Sandtrap Conglomerate, and Pleistocene(?) basalts are equivalent to our mesa-forming basalts.

The volcanic suite is strongly bimodal; rocks that have 55 to 71 weight percent SiO_2 are absent. Five volcanic units can be distinguished on the basis of age, geomorphic position, and petrography: the older basalts (18.7 and 16.5 m.y.), quartz-bearing basalts (13.7 and 12.4 m.y.), rhyolite lavas and tuffs (15.1 to 10.3 m.y.), mesa-forming basalts (13.1 to 19.2 m.y.), and megacryst-bearing basalts (3.6 to 6.8 m.y.). The basalts contain groundmass olivine and titanaugite phenocrysts and are alkali-olivine basalts. Most of the rhyolites contain more than 75 weight percent SiO_2.

The initial Sr isotopic composition of the basalts is: older basalts, 0.7077; quarts-bearing basalts, 0.7034; mesa-forming basalts, 0.7062; and megacryst-bearing basalts, 0.7035 and 0.7038. This evidence suggests that some of the basalts ($^{87}Sr/^{86}Sr_i$ = 0.703 to 0.704) are partial melts of upper mantle material. The chemical composition of some of the megacrysts in the megacryst-bearing basalts suggests a high-pressure mantle origin (4.4 to 15.8 percent Ca-Tsch and Mg/Mg+Fe* = 69.8 to 88.1 in clinopyroxenes, Al_2O_3 = 3.14 to 7.76 percent in titanomagnetites, presence of ferrian pleonaste). Whole-rock Mg/Mg+Fe* = 40.6 to 56.6 and the presence of phenocrysts in these basalts indicates crystal fractionation before eruption. Other basalts that have > $^{87}Sr/^{86}Sr_i$ 0.705 probably were derived from previously depleted lower crustal granulites. A very crude positive correlation between $^{87}Sr/^{86}Sr_i$ versus Sr and K/Rb and an inverse correlation between $^{87}Sr/^{86}Sr_i$ and Rb/Sr indicate that the high ^{87}Sr basalts are not contaminated with older crustal material. Partial melting from an isotopically vertically stratified upper mantle is also unsupported; the high-silica (quartz-bearing) basalts have low $^{87}Sr/^{86}Sr_i$.

The rhyolites have initial Sr isotopic ratios of 0.7093 and 0.7141. These ratios are higher than those of the basalts and indicate that the rhyolites were not differentiated from the basalts. Partial melting of 1.3 b.y.-old lower crustal material with Rb/Sr = 0.10 to 0.19 satisfactorily explains the isotopic ratios of the rhyolites. Granulite, which may constitute the lower crust in this part of Arizona, has Rb/Sr ratios similar to those required to produce the rhyolites.

The quartz-bearing basalts were derived from the mantle. The low (0.7034) $^{87}Sr_i$ precludes contamination by old crustal material, and high FeO and TiO_2 content indicate that dilution by Tertiary rhyolite did not occur. Like other quartz-bearing basalts in the Basin and Range Province, those in the Castaneda Hills area contain olivine. The quartz may be a high-pressure phenocryst (Nicholls and others, 1971), whereas the olivine crystallized at lower pressures.

Some of the rhyolites contain high (7 to 9 percent) K_2O and low Na_2O (0.8 to 2 percent). Harker diagrams indicate an apparent direct substitution of K for Na probably occurred during cooling and devitrification in the presence of an alkali-rich fluid. The groundmass feldspar concentrated K compared to the glass from which they crystallized.

In summary, the Miocene volcanic rocks in the Castaneda Hills area were generated by partial melting of upper mantle peridotite and partial to extensive melting of old, variably depleted lower crustal granulite. These melting events occurred over a relatively brief (19 to 7 m.y.) time interval. The production of basaltic and rhyolitic magma from the Earth's crust and mantle requires extremely heterogenous source regions. The mantle and crust have obvious compositional differences. In western Arizona, the lower crust also is compositionally heterogeneous due to varying degrees of depletion of the lower melting fraction, possibly during the Laramide orogeny. The eruption of crustal-derived basalt and rhyolite at the same time and in the same place suggests that compositional differences within the lower crust are remarkably abrupt. An additional factor affecting the degree of partial melting in the lower crust may be thermal inhomogeneities inherited from previous magmatic events. This would enable "warm", previously depleted granulite to produce basalts during the same Miocene thermal event in which "cool", undepleted granulite is producing rhyolite.

The bimodal volcanism and associated tectonism in the Castaneda Hills area represent a heating and distension event that affected the entire Basin and Range Province in the Miocene. In some areas, extensional deformation was manifested as low-angle listric faults within a thin suprastructure. Elsewhere, more "typical" and slightly younger high-angle normal faults penetrated to greater depths. The Basin and Range orogeny probably was caused by the complex interaction of inter- or back-arc spreading with the termination of subduction and lengthening of the San Andreas transform system. The detailed history is probably more complex because of crustal compositional and thermal inhomogeneities inherited from Paleozoic, Mesozoic, Laramide, and early- and mid-Tertiary deformational and magmatic events.

References Cited:

Lasky, S. G., and Webber, B. N. 1949, Manganese resources of the Artillery Mountains region, Mohave County, Arizona: U. S. Geol. Survey Bull. 961, 86p.

Nicholls, J., Carmichael, I.S.E., and Stormer, J.C., Jr., 1971, Silica activity and P total in igneous rocks: Contr. Min. and Pet., v. 33, p. 1-20.

Deformation Patterns in the Peninsular Ranges Batholith, San Diego County, California

by

V. R. Todd and S. E. Shaw

Introduction

This abstract reports on part of the Peninsular Ranges batholith of California and Mexico (Fig. 1). An older group of plutons (120 to 105 m.y., Silver and Chappell, 1979) was emplaced during an episode of deformation that produced steeply dipping structures with north-northwest and west-northwest trends (Fig. 2). Temperatures during deformation were high enough (upper amphibolite facies) for the plutonic rocks to recrystallize. Hornblende-pyroxene tonalite and gabbro intruded predominantly metavolcanic rocks in the western part of the area, and biotite ± muscovite granodiorite was abundant in the eastern part where wallrock inclusions are dominantly metasedimentary. Western plutons intruded their own volcanic suprastructure; they occur in bimodal, concentric complexes with volcanic rock. Eastern syntectonic plutons occur in anatectic migmatites with metasedimentary wallrock. Metamorphic grade and deformation generally increase eastward; plutonic textures range from synkinematic gneiss in the west to mylonite gneiss in the east. Large, high-strontium plutons intruded both western and eastern zones about 97 to 98 m.y. ago (Silver and Chappell, 1979) (Fig. 2). These plutons have undergone locally intense deformation within the study area. The major episode of deformation began sometime in Latest Jurassic or Early Cretaceous time and continued throughout, and after, intrusion of the early group of plutons (120 to 105 m.y.). Deformation continued locally for some time after 97 m.y. ago, particularly in the eastern part of the batholith.

Prebatholithic Setting

Wallrock inclusions in the western part of the batholith are similar in composition, relict textures and metamorphism to the Late Jurassic and early Cretaceous Santiago Peak Volcanics (Fife and others, 1967; Schoellhamer and others, in press). They are believed to be fragments of the volcanic terrane engulfed by Cretaceous magmas. In the eastern part of the study area, feldspathic metaquartzite and schist (metagraywacke) predominate (Fig. 2), but these rocks are rare in the western screens. Because the eastern wallrocks are undated, it is possible that rocks older than latest Jurassic are also present. Metavolcanic rocks typically are interlayered with metasedimentary rocks in wallrock inclusions as far east as the western Colorado Desert, and metamorphosed tuff-breccia grades into metaquartzite and metaconglomerate locally, indicating that the original contact was interfingering and gradational rather than tectonic.

Early (Syntectonic) Plutons

The composition of the early (syntectonic) plutons reflects the influence of wallrock composition. Pyroxene-hornblende tonalite plutons in the west are associated with metavolcanic wallrock inclusions, whereas biotite ± muscovite granodiorite plutons occur with metasedimentary inclusions in the eastern part of the area. A central transitional zone in which pyroxene-hornblende tonalite and related rocks are interlayered with biotite ± muscovite granodiorite coincides closely with the boundary between metavolcanic and metasedimentary wallrock terranes (Fig. 2).

Western syntectonic plutons: There are two major rock suites among the western syntectonic plutons: a variety of ultramafic and mafic rocks, principally olivine-pyroxene gabbro-norite and amphibole gabbro (Walawender, 1979) constitute the first suite, and a differentiated series of tonalitic rocks constitute the second (Fig. 3). Map relations and contacts on all scales indicate that mafic and tonalitic magmas were coeval. Mafic plutons in the study area occur in steeply-dipping, sheeted complexes with plutons of the tonalitic suite (Fig. 2). In two ring complexes, marginal hornblende gabbro is fine-grained and porphyritic against granitic rocks, and fragments of metavolcanic rock, locally grading into gabbro, separate the plutonic sheets. Contacts locally suggest chilling of mafic magma against granitic magma, followed by chilling of granitic magma against solidified gabbro (Todd and Shaw, 1979).Gradational relations between felsic and mafic volcanic wallrocks and granitic and mafic plutons, respectively, suggest that western plutons of the batholith were genetically related to the volcanic rocks into which they were intruded.

Eastern syntectonic plutons: The early (syntectonic) biotite ± muscovite plutons of the eastern part of the study area are distinguished by reduced biotite, excess modal quartz, and accessory ilmenite and aluminosilicate minerals. Initial $^{87}Sr/^{86}Sr$ values for a suite of these eastern rocks are significantly higher than those reported by Silver and Chappell (1979) for the western pyroxene-hornblende tonalite plutons (Shaw and Todd, work in progress). The micaceous granodiorite plutons tend to be more deformed than plutons of the pyroxene-hornblende tonalitic suite, but the deformation fabric is continuous across the two types in the central transitional zone implying that the same event affected both terranes. The greater deformation of the eastern plutons probably resulted in part from relatively high water pressures due to metamorphic dewatering of the abundant metasedimentary inclusions, but, in general, regional strain must also have increased eastward. Furthermore, the relatively coarser grain size and high degree of metamorphic differentiation of wallrock inclusions associated with the biotite ± muscovite granodiorite plutons suggest that the latter formed at greater depths in the crust than did the western plutons, depths where ductile deformation would have been enhanced.

The eastern plutons have not yet been dated. In the central transitional zone the eastern plutons show overlapping age relations to plutons of the pyroxene-hornblende tonalitic suite. Biotite granodiorite with actinolized hornblende relicts locally grades into biotite-hornblende tonalite. For these reasons, the western and eastern syntectonic plutons are believed to be contemporaneous.

Later Plutons

Large plutons of relatively undeformed, leucocratic tonalite and granodiorite intruded the syntectonic terrane about 97 to 98 m.y. ago (Fig. 2). These plutons are significantly higher in strontium than the early group suggesting that the former were derived from source materials that already had been modified by production of early magmas (Todd and Shaw, 1979) (Fig. 3). Large apophyses of the later plutons that occur within the early (syntectonic) terrane in the southern part of the study area (Fig. 2) are marginally deformed with the same fabric as that of the surrounding syntectonic plutons.

Structure and Metamorphism

The distinctive batholithic structure in the study area probably resulted from intrusion during an extended period of deformation that began prior to, and outlasted, intrusion. The typical pluton has the form of a sub-vertical sheet or lensoid body ranging from several km to more than 25 km in outcrop length. The sheets clearly are intrusive bodies, yet internal foliation structures (S_1) concordant to pluton walls were produced by breakdown and recrystallization of mineral grains (solid-state or ductile flow).

Synkinematic metamorphism began prior to intrusion of the tonalitic suite of the western part of the batholith, because these plutons intruded along axial plane foliation (S_1) in wallrocks and into the hinge areas of isoclines (Fig. 2). This metamorphism was the major recrystallization affecting wallrocks, in which original sedimentary structures locally are preserved. Steeply-dipping penetrative metamorphic foliation (S_1) and down-dip lineation are concordant between pluton and wallrock inclusion. Isoclinally-folded wallrock-pluton contacts are ubiquitous (F_1), and axial planes are parallel to regional foliation (S_1). The structural relations between plutons and wallrocks require that the two were in essentially the same physical state (Berger and Pitcher, 1970). In the eastern part of the study area, S_1 and F_1 were refolded and original sedimentary and volcanic structures were obliterated (polyphase folding).

Mylonitic Rocks

The gneissic fabric of the plutonic rocks grades locally to mylonite gneiss with thin (5 cm) zones of black aphanitic mylonite. Zones of mylonite gneiss are broadest and most numerous in the eastern part of the study area. The steeply plunging down-dip lineation that was observed in western plutons and wallrock inclusions was intensified in mylonitic rocks in the east. In the western part of the area, zones of mylonite gneiss are relatively narrow and discrete, and they trend parallel to, and crosscut the regional fabric. Discordant north-northeast-trending mylonitic zones are associated with small, predominantly right-lateral flexures less than 1 km in amplitude. In the eastern part, the zones are broader, more continuous, and generally concordant with batholithic structure. They appear to be geographically continuous with the Santa Rosa mylonite belt (Sharp, 1968; Theodore, 1970). In the study area, mylonite gneiss is developed in both western and eastern-type plutons of the early group, and in parts of later leucotonalite plutons. The intercalated metamorphic wallrocks invariably were not mylonitized. Structural and intrusive relations between mylonitic plutons and adjacent synkinematically recrystallized wallrocks suggest that the two underwent deformation at about the same time but that strain was concentrated in plutons that were still partly magmatic.

Significance for Tectonic Models of Batholithic Evolution

The findings of this study indicate that a volcano-plutonic arc was initiated in the vicinity of the western continental margin in Latest Jurassic time. Synkinematic metamorphism began in volcanic and volcaniclastic deposits and continued during the period from 120 to 105 m.y. ago in plutons that had intruded the boundary between the volcanic arc and volcaniclastic basin. Deformed ring structures involving mafic and granitic rocks may have been feeders for flows and breccias of the volcanic field. By 97 m.y. ago, the arc had migrated eastward, producing large, homogeneous, strontium-rich plutons that show only local deformation. Plutonic gneisses that enclose minor mylonitic zones grade eastward to broad, discontinuous zones of mylonite gneiss. Structures between the two terranes are generally concordant, but local discordance indicates that ductile mylonitization continued for a considerable time after batholithic emplacement and that regional stress directions changed. The west-northwest-trending deformation structures of the western part of the batholith are anomalous for the Peninsular Ranges batholith. Limited data suggests re-orientation of these trends during continuing and later deformation to the more common north-northwest trends. Foliation and lineation in the study area dip steeply (75 to 90 degrees) to the east, northeast, and north (sub-vertical tectonic transport) but limited mapping in the Colorado Desert indicates that to the east, dips became moderate to gentle. It is not clear whether this apparent change relates to broad folding, or to a change in geometry of shearing.

References Cited

Berger, A. R., and Pitcher, W. S., 1970, Structures in granitic rocks: a commentary and a critique on granitic tectonics: Proceedings of the Geological Association of London, v. 81, p. 441-461.

Fife, D. L., Minch, J. A., and Crampton, P. J., 1967, Late Jurassic age of the Santiago Peak Volcanics, California: Geological Society of America Bulletin, v. 78, p. 299-304.

Schoellhamer, J. E., Vedder, J. G., Yerkes, R. F., and Kinney, D. M., in press, Geology of the northern Santa Ana Mountains: U.S. Geological Survey Professional Paper, in press.

Sharp, R. V., 1968, The San Andreas fault system and contrasting pre-San Andreas structure in the Peninsular Ranges of southern California (abs.) in Dickinson, W. R., and Grantz, A. (eds.), Conference on Geologic Problems of San Andreas fault system, Stanford University, September 14-16, 1967, Proceedings: Stanford University Pubs. Geol. Sci. v. 11, p. 292-293.

Silver, L. T., and Chappell, B., 1979, Some petrological, geochemical and geochronological observations of the Peninsular Ranges batholith near the International Border of the U.S.A. and Mexico: in Abbott, P. L., and Todd, V. R. (eds.), Mesozoic Crystalline Rocks, Field Trip Guidebook, 92nd Annual Meeting, Geological Society of America, San Diego, California, p. 83-110.

Theodore, T. G., 1970, Petrogenesis of Mylonites of High Metamorphic Grade in the Peninsular Ranges of southern California: Geological Society of America, Bulletin, v. 81, p. 435-450.

Todd, V. R., and Shaw, S. E., 1979, Structural, metamorphic and intrusive framework of the Peninsular Ranges batholith in southern San Diego County, California: in Abbott, P. L., and Todd, V. R., (eds.), Mesozoic Crystalline Rocks, Field Trip Guidebook, 92nd Annual Meeting, Geological Society of America, San Diego, California, p. 177-231.

Walawender, M. J., 1979, Basic plutons of the Peninsular Ranges batholith, southern California: in Abbott, P. L., and Todd, V. R., (eds.), Mesozoic Crystalline Rocks, Field Trip Guidebook, 92nd Annual Meeting, Geological Society of America, San Diego, California, p. 151-162.

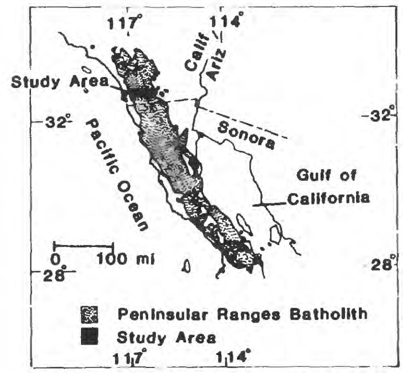
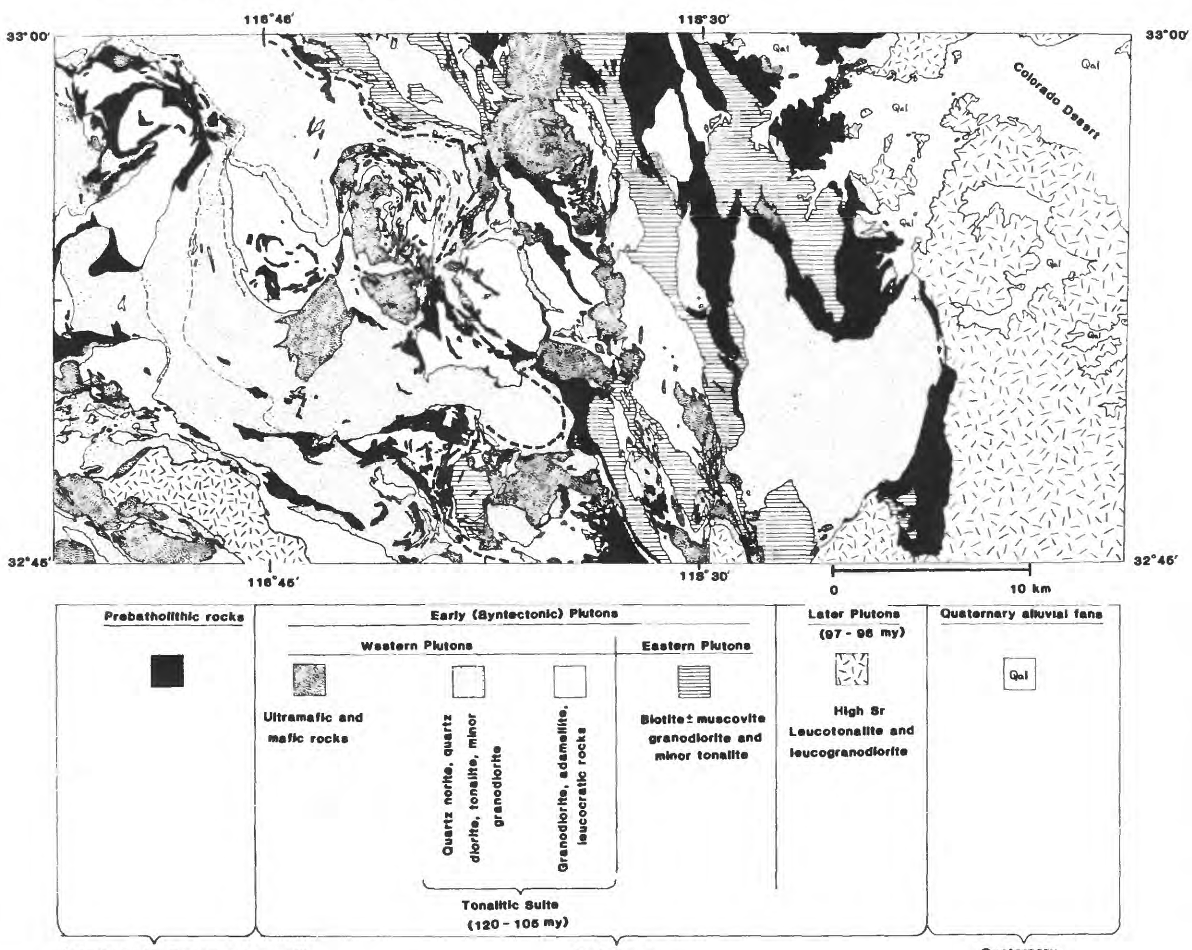


Fig. 1 Peninsular Ranges Batholith in southern California and Baja California

Fig. 2 Simplified geologic map of study area. Solid lines are contacts, dashed lines separate subunits of tonalitic suite. Faults omittad. Deformation structures in syntectonic plutons and metamorphic screens generally parallel contacts. Heavy broken line marks western limit of biotite ± muscovite granodiorite plutons and approximate boundary between metavolcanic and metasedimentary wallrocks.



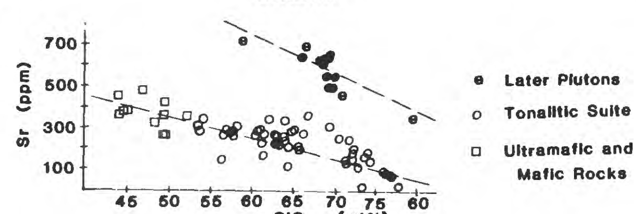


Fig. 3 Strontium - silica variation diagram for selected plutonic rocks.

LATE CRETACEOUS TO LATE TERTIARY BASE- AND PRECIOUS-METAL MINERALIZATION, SOUTH-CENTRAL, ARIZONA

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Three distinct base- and precious-metal episodes of mineralization occur in the Papago Indian Reservation and Ajo area, south-central Arizona. The overall range of these episodes is Late Cretaceous to late Tertiary. Copper±molybdenum porphyry systems of the typical Late Cretaceous to early Tertiary age span, an inferred porphyry molybdenum(?) system of early Miocene age, and early to middle Tertiary epithermal fissure-vein systems comprise these episodes. Delineation of these episodes has also involved work by T. G. Theodore, J. A. Briskey, and R. A. LeVeque, U.S. Geological Survey.

The Arizona copper province includes the most important concentrations of large porphyry copper±molybdenum deposits in North America. In the Papago-Ajo area, several porphyry copper±molybdenum deposits are currently being mined, Ajo, Lakeshore, and Silver Bell; whereas other prospects are well known (e.g. Vekol Mountains). Host rock lithologic units have affinities for geologic terranes of central Arizona and are part of the northern Papago terrane of Haxel and others (1980). Late Cretaceous to early Tertiary hornblende-biotite quartz monzonite to granodiorite, and porphyry are associated genetically with the deposits. Sulfide mineralization is present in stockworks, supergene enrichment zones, and in carbonate host rocks. Classic porphyry copper alteration assemblages, potassic, phyllic, argillic, and propylitic, are distributed about the porphyry centers.

An inferred molybdenum(?) porphyry system in the Cimarron Mountains is tectonically and metallogenetically distinct from the Late Cretaceous to early Tertiary copper±molybdenum porphyry deposits. This porphyry system is centered about a Miocene dacite porphyry that occurs in the structural center of a possible caldera complex (Briskey and others, 1978; Dockter and Keith, 1978). An 11-km-across ring fracture/fault system outlines the complex. In the complex, widespread hydrothermal alteration has been recognized in the Precambrian Pinal Schist and quartz monzonite to tonalite (Dockter and Keith, 1978; Haxel and others, 1980), and the Miocene dacite porphyry. The rocks are extensively propylitized and pyritically altered around a core of potassic alteration centered on the dacite porphyry. Hydrothermal fluorite occurs in veins. Phyllic alteration and silicification is superposed on the potassic assemblages. Secondary copper minerals and vein galena have been observed, but no molybdenite has been identified as yet. The caldera complex also is defined by volcanic rocks that are younger than the porphyry system.

Early to middle Tertiary epithermal fissure-vein deposits are areally extensive in the southern Papago-Ajo area, spatially and temporally separate from and genetically unrelated to the known porphyry systems

Fissure-vein deposit districts are present in the Baboquivari Mountains, Comobabi Mountains, Quijotoa-Brownell Mountains, Gunsight Hills, and several ranges in Organ Pipe Cactus National Monument. Some of the fissure-vein deposits previously have been considered to be related to porphyry systems (Keith, 1978); but the characteristics and timing of the fissure-veins indicate that they are best considered to be part of a regional Eocene metallogenic episode. (Tosdal and Briskey, 1981). Moreover, they are apparently a northward lobe of the middle Tertiary epithermal fissure-vein province of the Sierra Madre Occidental of Mexico.

Host rocks for the Eocene fissure-veins are early Tertiary and older (>55 m.y.), differ among districts, and are part of the southern Papago terrain of Haxel and others (1980). No known contemporaneous plutonic or volcanic rocks exist to which the Eocene fissure-veins can be related. An exception exists in a single district of the Baboquivari Mountains (Allison Camp) where fissure-veins cut Miocene hypabyssal dikes.

Texturally, the fissure-veins are characterized by polyphase cavity filling of gangue and ore in breccias and shear zones. Vein textures can be divided into three main types: banded, shear, and crackle breccias. Commonly these have cockscomb, cockade, drusy, and hydrothermal exfoliation textures. Within districts, the veins closely follow the existing regional fault and fracture patterns.

Hypogene ore minerals present in the fissure-veins include one or more of the following: galena, chalcopyrite, chalcocite, bornite, free gold, and less commonly stromeyerite, argentite, sphalerite, molybdenite, tetrahedrite, and scheelite (Williams, 1963, Keith, 1974). Hypogene ore minerals consistently fill open spaces and are late in the vein paragenesis. Supergene oxidation has produced variable amounts of carbonate, silicate, oxide, and sulfate minerals (e.g. Williams, 1963).

Gangue minerals are: milky quartz, sulfides, fluorite, barite, tourmaline, calcite, specular hematite, magnetite, manganese oxide minerals, and epidote. In some districts, barite, fluorite, and manganese oxide minerals have been mined in addition to the base and precious metals (Keith, 1974). Sericitic (white mica+quartz±pyrite), less commonly argillic (kaolinite+quartz), and rarely adularia or phlogopitic biotite alteration occur immediately adjacent to the veins. Propylitic assemblages (chlorite+ epidote±calcite) are distal alteration phenomena to the veins. Moderate to intense silicification and weak to moderate albitization occur immediately adjacent to the veins and diminishes in intensity outward. Fluid inclusions are a two-phase type and probably characterized by moderate salinities.

These Eocene fissure-veins are spatially related to but slightly younger than terranes affected by a pronounced Late Cretaceous and early Tertiary regional orogenic event (Tosdal and Briskey, 1981; Haxel and others, 1980; Haxel, 1981). Ore fluids probably evolved during the waning stages of this regional thermal episode. Upward ore fluid migration, hydrothermal circulation, and fissure-vein deposition in dilation fractures and faults occurred during the onset of the extensive Eocene uplift and accompanying erosion throughout the Papago-Ajo area.

References Cited

Briskey, J. A., Haxel, Gordon, Peterson, J. A., and Theodore, T. G., 1978, Reconnaissance geologic map of the Gu Achi quadrangle, Pima County, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-965, scale 1:62,500.

Dockter, R. D., and Keith, W. J., 1978, Reconnaissance geologic map of the Vekol Mountains 15-minute quadrangle, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-931, scale 1:62,500.

Haxel, Gordon, 1981, Late Cretaceous and early Tertiary orogenesis, south-central Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 13, (in press).

Haxel, Gordon, Wright, J. E., May, D. J., and Tosdal, R. M., 1980, Reconnaissance geology of the Mesozoic and Lower Cenozoic rocks of the southern Papago Indian Reservation, Arizona. A preliminary report: Arizona Geological Society Digest, v. 12, p. 17-29.

Keith, Stanley B., 1978, Origins of Arizona copper deposits--Hypotheses: Arizona Bureau of Geology and Mineral Technology, v. 8, nos. 1 and 2.

Keith, Stanton B., 1974, Index of mining properties in Pima County, Arizona: Arizona Bureau of Mines Bulletin 189, 156 p.

Tosdal, R. M., and Briskey, J. A., 1981, Middle Tertiary fissure-vein base- and precious-metal mineralization, Papago Indian Reservation, south-central Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 13 (in press).

Williams, S. A., 1963, Oxidation of sulfide ores in the Mildren and Steppe mining districts, Pima County, Arizona: Economic Geology, v. 58, p. 1119-1125.

COLORADO PLATEAU MARGIN IN THE WEST CLEAR CREEK REGION OF CENTRAL ARIZONA.

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Miocene and Pliocene(?) volcanism in concert with extensive erosion and normal faulting has sculptured the Colorado Plateau margin in central Arizona. Mapping in the eastern Verde Valley supports the conclusion of Pierce and others (1979) that the elevated Plateau margin existed before mid-Miocene time. West Clear Creek cuts through the southwestern margin of the Plateau for nearly 40 km and debouches westward into the Arizona transition zone that separates the Plateau and the Basin and Range provinces. It exposes a cross section of upper Tertiary volcanic rocks, mainly alkali-olivine basalts that overlie Lower Permian sedimentary rocks that dip gently westward on the southwestern flank of the Mormon Mountain anticline of Twenter and Metzger (1963). The age of folding has not been documented but is inferred to be Laramide by analogy with nearby structures in the Plateau.

Normal faults subparallel to the Plateau margin have enhanced the structural drop to the west. Of 53 faults mapped, 30 are down to the west or southwest and 23 are down to the east or northeast with a net throw of 380 m down to the west. An additional 300 m of structural lowering is accounted for by westward dip. These relations, including two of the more important faults, are illustrated in figure 1. The Cash Tank fault predated the bulk of the volcanism, as shown by dramatic thickening of the basalts from <30 m on the Plateau proper to >450 m west of the fault. A few andesites, silicic ash flows, and abundant pyroclastic basaltic units are manifestations of the increased eruptive activity within the thick western part of the volcanic pile. Near the bottom of the pile, a late Miocene age of 10.6 ± 0.3 m.y. for a basalt has been determined by Pierce and others (1979); thus major faulting and at least 450 m of relief characterized this part of the Plateau margin before that time.

A broad paleovalley west of the Cash Tank fault and about 10 km wide and 400 m deep was carved at or inside the Plateau margin before volcanic infilling (figure 1). The basal deposits in this valley are coarse conglomerates with clasts derived mostly from local Permian rocks and with sparse clasts of Precambrian and lower Paleozoic rocks; the latter may be reworked from older Plateau rim gravels as proposed by Pierce and others (1979) for this area and for the Fort Apache and Oak Creek Canyon areas. The apparent westward slope of the conglomerates along West Clear Creek (not believed to be tilted) and an occurrence of southwestward-dipping crossbeds support this interpretation. Alternatively, local concentrations of coarse, poorly sorted Mississippian and Devonian carbonate fragments suggest a local bedrock source; however, the nearest outcrops of these rocks are at least 20 km to the southwest and southeast. In either interpretation, this segment of the Plateau margin was already defined when the conglomerate was deposited. Inferred faulting west of Bull Pen Ranch, during and after volcanism, dropped the western edge of the volcanic pile down toward the Verde Valley which received coarse sediments from the surrounding highlands and lacustrine deposits toward its interior during Miocene and Pliocene time (Bressler and Butler, 1978).

A simpler history of Plateau margin development is documented by continued mapping 8 km to the north near Walker Mountain (figure 2). The escarpment is 430 m high and is a product almost entirely of erosion. It existed prior to volcanism, was mantled by basalt in the Miocene or Pliocene, and has retreated eastward approximately 2 km due to subsequent erosion.

In summary, the high-standing Plateau rim and west-facing escarpment existed at least as early as late Miocene, and, in view of the extensive tectonic and erosional record that preceded volcanism, it probably existed well before that time.

REFERENCES CITED

Bressler, S. L., and Butler, R. F., 1978, Magnetostratigraphy of the late Tertiary Verde Formation, central Arizona: Earth and Planetary Science Letters, v. 38, p. 319-330.

Twenter, F. R., and Metzger, D. G., 1963, Geology and ground water in Verde Valley--the Mogollon Rim region, Arizona: U. S. Geological Survey Bulletin 1177, 132 p.

Pierce, H. W., Damon, P. E., and Shafiqullah, M., 1979, An Oligocene(?) Colorado Plateau edge in Arizona: Tectonophysics, v. 61, p. 1-24.

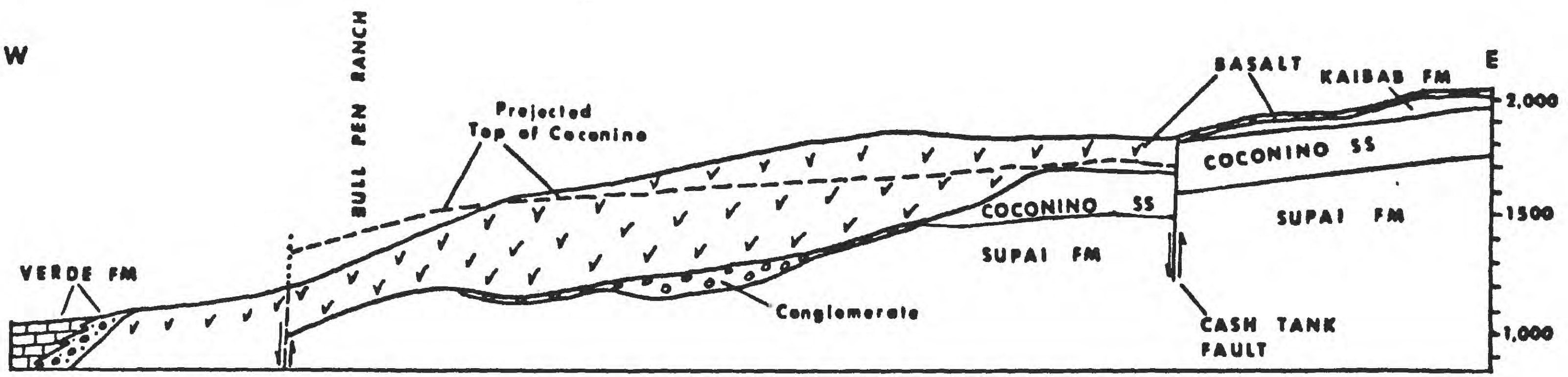

Figure 1. Geologic cross section of West Clear Creek Canyon area, Arizona.

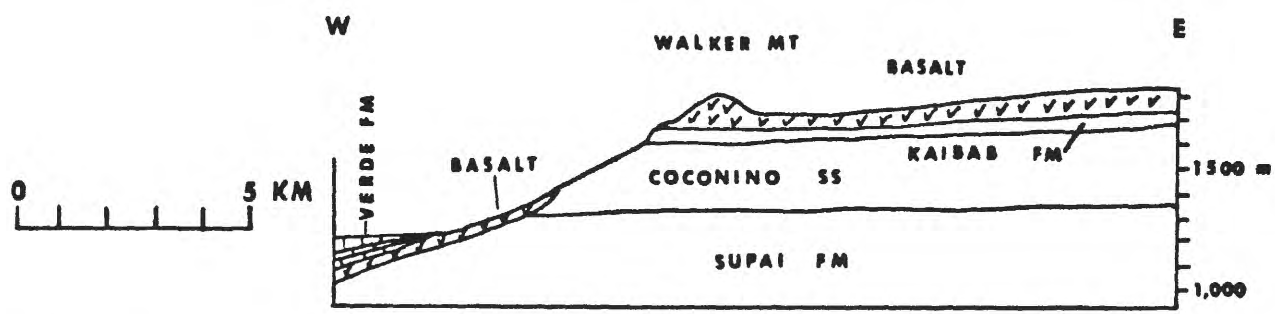

Figure 2. Geologic cross section of Walker Mountain area.

A GARNET-TWO-MICA GRANITE, COYOTE MOUNTAINS, SOUTHERN ARIZONA: GEOLOGIC SETTING, URANIUM-LEAD ISOTOPIC SYSTEMATICS OF ZIRCONS, AND NATURE OF THE GRANITE SOURCE REGION.

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The Pan Tak Granite which makes up much of the Coyote Mountains (35 km southwest of Tucson) consists chiefly of biotite or muscovite-biotite granite and garnet-muscovite or garnet-biotite granite and associated pegmatite, and is representative of the widespread garnet-two-mica granites of south-central Arizona. None of these granites are associated with any hornblende bearing rocks or any granodioritic or tonalitic rocks, and thus apparently do not belong to a normal compositionally expanded differentiation sequence. Based on essential and varietal mineralogy, and uniform compositional simplicity, the Pan Tak and related two-mica-garnet granites correspond to granitoids of presumed crustal origin (S-type).

Structural and geochronologic relationships indicate that the Pan Tak Granite was intruded into Jurassic plutonic rocks and Paleozoic metasedimentary rocks during a Late Cretaceous-early Tertiary (58 m.y.b.p.) thermal, magmatic and deformational episode, which imparted a regional crystalloblastic foliation to the granite and its country rocks. This orogenic episode was manifested by the overthrusting of crystalline rocks, regional metamorphism, and intrusion of the garnet-two-mica granites. Subsequent to this event, the Pan Tak Granite was locally mylonitized and brecciated during a latter (post 58 m.y. - pre 25 m.y.) metamorphic episode. The two metamorphic fabrics now found within the Pan Tak Granite differ in age, distribution, style and orientation.

Uranium-lead isotopic ratios of five size fractions of zircons separated from the Pan Tak Granite have been analyzed. All zircon fractions are discordant, but define a linear data array with a lower concordia intercept of 58 ± 3 m.y. and an upper concordia intercept of approximatley 1.1 b.y. (Fig. 1). $^{207}Pb^{*}/^{206}Pb^{*}$ apparent ages increase progressively up the chord from 214 m.y. (<325 mesh fraction) to 434 m.y. (>100 mesh fraction). All zircon size fractions analyzed contain sharply euhedral normally zoned crystals, but in a general way the larger size fractions contain progressively more crystals that contain partially resorbed turbid cores. The isotopic systematics, zircon morphologies and geologic relations indicate that the chord defined by the isotopic data is a mixing line between relict Precambrian zircons and zircons formed 58 m.y. ago during crystallization of the granite. Furthermore, geologic and isotopic evidence indicates that the older Precambrian zircon component was not assimilated from the country rocks, but rather inherited from the source region of the granite. This source material was probably the 1.7 to 1.4 b.y.-old crystalline basement of south-central Arizona. Generation of the Pan Tak Granite and related granites by crustal anatexis was one aspect of the Late Cretaceous-early Tertiary (Laramide) orogenic episode that affected this region of southern Arizona.

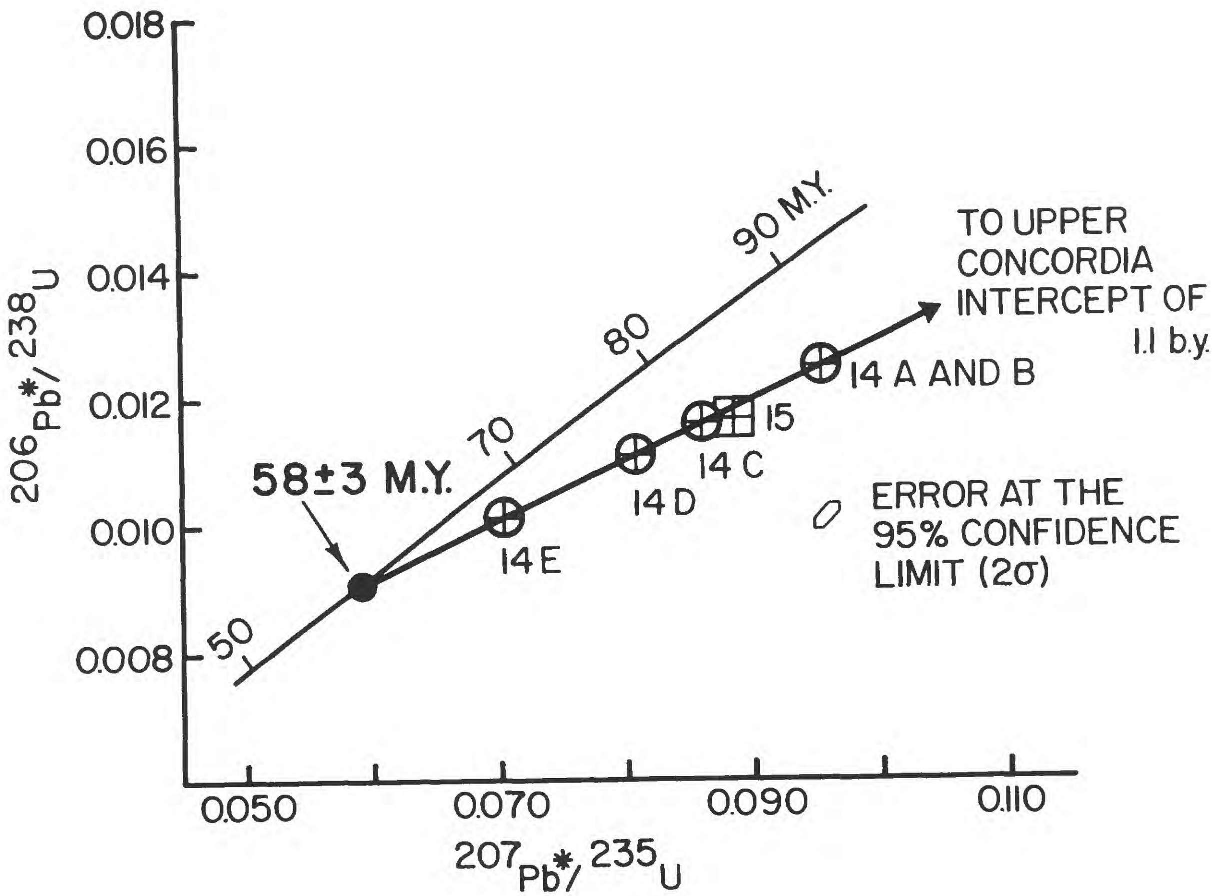

Figure 1. Concordia diagram of zircon size fractions from the Pan Tak Granite (14 A-E) and one related pluton; the Granite of Gu Chuapo (15). Letters A-E refer to size fractions of: > 100 mesh; >200, < 100 mesh; < 200, > 325 mesh; < 200 mesh; and < 325 mesh, respectively. Note that fractions 14A and 14B plot as one point at the scale of this figure.

GEOLOGY AND STRUCTURE OF THE PARADISE RANGE, MOJAVE DESERT, CALIFORNIA

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The Paradise Range is located in the Lane Mountain 15' quadrangle in California, 20 miles northeast of Barstow. The rock sequence in the map area includes three units of metasedimentary rocks that are in possible fault contact with each other, and are intruded by an older gabbro to tonalite intrusive suite and a younger quartz-monzonite pluton.

Unit 1, the structurally lowest metasedimentary unit, contains banded actinolite-quartz hornfels, with thin interlayers of pelitic schist and pelitic hornfels. It is structurally overlain by Unit 2, which is composed of thin units of recrystallized orthoquartzite and pelitic schist. Unit 3, the structurally highest unit, is a package of calc-silicate and marble interbedded and interlayered with banded hornfels, pelitic schist and quartzite.

The metasedimentary rocks in the range form an east-west trending, south dipping homocline, which is the southern limb of an antiformal dome caused by the emplacement of the younger quartz-monzonite pluton. Smaller-scale structures in the metasedimentary rocks point to two definite deformational events, and possibly a weak third event. The first two deformations were coaxial: the fold axes are oriented S54E, 49SE. The first folding event was isoclinal and caused transposition of bedding into parallelism with the axial planes of these folds that are today oriented N88E, 48SE. The second event produced open to tight folds whose axial planes are now oriented N52W, 38NE. The third event produced only gentle to very open folding of the previous structures. Its axis is oriented N72E, 40NE.

The mineralogy and texture of the metasedimentary rocks suggests two metamorphic events. The first occurred during the first deformation, and was of amphibolite grade. This was overprinted by a younger contact metamorphism associated with the emplacement of intrusive rocks in the range, and was also of amphibolite grade.

Work in progress by E.L. Miller and J.F. Sutter indicates that the older gabbro to tonalite suite in the range is at least 142my old and is similar to plutonic rocks in adjacent areas that are at least as old as 148my ($^{40}Ar/^{39}Ar$, hornblende). Severe argon loss from these rocks was probably due to the emplacement of younger, 81my old quartz-monzonite ($^{40}Ar/^{39}Ar$, biotite).

The metasedimentary rocks of the Paradise Range are lithologically correlative to similar rock sequences in the El Paso Mountains and the Goldstone tracking station area. Poole and Christiansen (1980) have dated graptolites in a eugeoclinal quartzite-bearing sequence in the El Paso Mountains as Ordovician. On the basis of age and lithology, this sequence correlates with quartzites in the Valmy or Vinini sequences of the Roberts Mountain allochthon in Nevada. Quartzites in Unit 2 in the Paradise Range are lithologically similar to the Ordovician quartzites in the El Paso Mountains, and therefore may also be correlative with parts of the Roberts Mountain allochthon.

The rocks in Unit 3 in the Paradise Range are also lithologically similar to part of the El Paso sequence, dated as Ordovician (Carr, personal comm., 1980). Unit 3 is also similar, however, to part of the Coyote group at Lane Mountain, which conformably underlies a conglomerate containing Penn(?) to Permian(?) fossils (Rich, 1971). Thus, the correct age and correlation for the Paradise Range Unit 3 cannot be resolved at this time.

Unit 1 shows lithologic similarities to part of the sequence in the El Paso Mountains. However, no ages have been assigned to those rocks, so the age of Unit 1 is unknown.

The metasedimentary rocks of the Paradise Range, and the rocks with which they correlate, are dissimilar to miogeoclinal and cratonal Paleozoic sequences present in the eastern and southwestern Mojave Desert. This would point to these rocks occurring either as an extension of the Antler orogenic belt into the northwest Mojave, or as part of a fault-bound sliver associated with a major left-lateral strike-slip fault which truncated the western edge of the continental margin in Permo-Triassic time (Davis, et. al., 1978).

REFERENCES

Davis, G.A., Monger, J.W.H., and Burchfiel, B.C., 1978, Mesozoic construction of the Cordilleran "collage," central British Columbia to central California, in Howell, D.G. and McDougall, K.A., eds, Mesozoic paleogeography of the western United States: Soc. Econ. Paleontologists and Mineralogists, Pacific Sec., Pacific Coast Paleogeography Symposium 2, p. 1-32.

Poole, F.G. and Christiansen, R.L., 1980, Allochthonous lower and middle Paleozoic eugeosynclinal rocks in the El Paso Mountains, northwestern Mojave Desert, California: Geol. Soc. America Abstracts with Programs, v. 12, no. 3, p. 147.

Rich, M., 1971, Fusulinids from central Mojave Desert and adjoining area, California: Jour. Paleontology, v. 45, p. 1022-1027.

THE TIMING AND STYLE OF CENOZOIC DEFORMATION IN THE BASIN AND RANGE PROVINCE OF SOUTHWESTERN ARIZONA INTERPRETED FROM GEOLOGIC EVENTS ALONG THE COLORADO PLATEAU MARGIN

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The relative stability of the thick Colorado Plateau block appears to have "damped out" all but the most significant Cretaceous to Pliocene tectonic impulses that apparently propagated eastward from the Mohave Desert region. It is assumed that the most significant changes in the relatively undeformed Cenozoic deposits on the plateau were produced by the major structural events affecting the broader region bordering the southwest margin of the plateau. Furthermore, any regional Cenozoic sedimentary or volcanic unit that can be shown to overlap the boundary of the two provinces is especially valuable for contrasting the style of subsequent deformation and its intensity across the region.

Young (1979) has recently reviewed and updated data bearing on the multiple deformational events that can definitely be inferred from the Cenozoic geology along the Colorado Plateau margin. Intrusives on or near the plateau edge south of Lake Mead demonstrate an early Laramide event that raised the edge of the plateau and initiated the northeast regional drainage (Mohave peneplain or Powell surface of Davis, 1930) which culminated in the deep erosional channels preserved as remnants incised into the upturned margin of the modern plateau. A period of relative structural inactivity and erosion was terminated by events associated with reactivation of the plateau monoclines, generally constrained to have been formed intermittently between Cretaceous and late Eocene time across the plateau (Young, 1979). In addition to the evidence for a significant time interval between these early Tertiary structural events, there is clear evidence of a long interval of weathering separating fluvial gravels in buried valleys that underlie the Oligocene-Miocene volcanic rocks on the plateau. Exposures and geophysical well logs in the Truxton Valley-Peach Springs Canyon area clearly show that fluvial gravels derived from uplifted basement rocks west of the plateau were subsequently weathered to depths of over 30 meters prior to the onset of regional middle Tertiary volcanism. This deep weathering is assumed to represent a late Eocene to Oligocene interval of structural quiescence preceding the onset of Basin and Range extensional tectonics and volcanism. Late Oligocene volcanic flows originating west of the modern plateau but flowing onto it provide the first indirect evidence of renewed tectonic activity following the post Laramide stable(?) interval.

In middle Miocene time the Peach Springs Tuff (Young and Brennan, 1974) was erupted across an area stretching from Kingman eastward to Seligman, Arizona, and from the north end of the Cerbat Mountains southward to the Riverside Mountains southwest of Parker, Arizona, (Dickey et al., 1980). The recent extending of the boundaries of this widespread ashflow tuff beyond the study area of Young and Brennan (1974) by Dickey et al. (1980), Lucchitta (written communication), and Goff (1979) makes it more useful

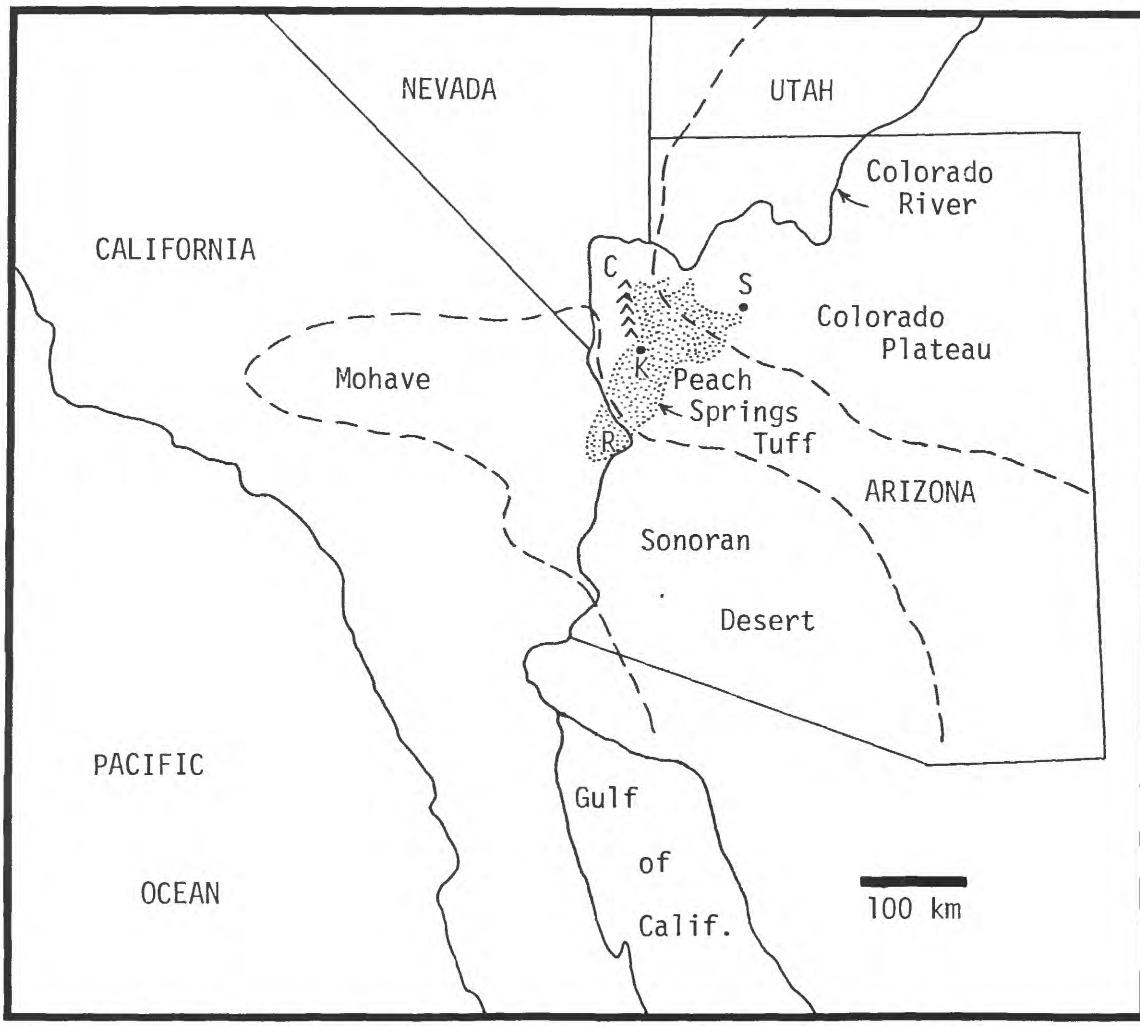

Figure 1. Approximate outcrop area of the Peach Springs Tuff. S = Seligman, K = Kingman, R = Riverside Mountains, C = Cerbat Mountains.