A Contribution to the Structural History of the Vidal-Parker Region, California and Arizona

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1430

Prepared in cooperation with the
U.S. Nuclear Regulatory Commission

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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By W. J. CARR

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A report concerning stratigraphy, structure, and geophysics of a region within
the eastern Mojave Desert and Mojave-Sonoran structural-physiographic belt,
wherein tectonic activity has occurred at a very low rate since
late Miocene time. Important structural activity of Tertiary age
culminated and concluded in a
major regional episode of detachment faulting

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A CONTRIBUTION TO THE STRUCTURAL HISTORY OF THE VIDAL-PARKER REGION, CALIFORNIA AND ARIZONA

By W. J. Carr

ABSTRACT

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 done in support of geologic evaluation of the region for proposed nuclear power generating facilities.

Several maps are presented, including 1:125,000-scale geologic map, and regional compilations of geology, gravity, and aeromagnetics at 1:500,000.

Physiography, geology, and geophysics combine to delineate a northwest-trending zone about 100 km wide, here named the Mojave-Sonoran Belt. This structural-physiographic feature can be viewed as a southeastward extension of the Walker Lane Belt of western Nevada.

Rocks of Precambrian, Permian, Cretaceous, Miocene, Pliocene, and Quaternary age have been identified in the Vidal-Parker region. All the pre-Tertiary rocks have undergone 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 sequence of late Paleozoic rocks, mostly of Permian age, has been recognized in several areas in the region. This sequence is 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 with 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 unit occurs above late Paleozoic rocks in several areas, and it is believed to be Mesozoic in age. Potassium-argon and fission-track dates record a minimum age of early Tertiary, however. On the other hand, rocks of this unit differ in character from other Mesozoic(?) rocks in the region.

Granite grading abruptly into granite gneiss is abundant in the region. These rocks have been dated as Late Cretaceous by potassium-argon techniques.

Tertiary rocks of the Vidal-Parker area are both Miocene and Pliocene, but nearly all the volcanic rocks are Miocene. The Tertiary stratigraphy is highly complex, units are discontinuous, and changes are abrupt. Many pronounced unconformities occur. Breccias and megabreccias are a prominent feature of the lithology. 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. A map of the known localities of the tuff shows a predominant northeast-southwest distribution, with a possible source southwest of Kingman, Ariz.

Sedimentary material, ranging from megabreccia to lacustrine limestone, dominates the Tertiary section in most areas. 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 unit of detrital material 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 late Miocene and 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, of intermediate-age fan deposits displaying varying degrees of soil and desert varnish formation, and of younger alluvium related to present drainage. Ages of these units are imprecise, but the oldest is probably Pliocene and Pleistocene; one of the more prominent deposits of intermediate age 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 this area the lineament is here named the Mojave-Sonoran Belt. The northeast edge 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 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 evidence exists 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 aeromagnetic and gravity maps as a scarcity of pronounced linear gradients or anomalies. The combination of less volume of 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 that existed in 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 include (1) restriction of structural disturbance to a relatively short interval of time, between 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 province.

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, 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-and-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.

Pliocene-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.

INTRODUCTION

PURPOSE OF INVESTIGATION

Work leading to this report is an outgrowth of the interest of southern California power companies in the eastern Mojave Desert as a site for nuclear reactors for generation of electricity. In their search for areas of tectonic stability, these companies recognized the potential of this area for reactor siting. The Vidal, Calif., site (fig. 1) selected by Southern California Edison Company is about 16 km west of Parker, Ariz. Extensive investigations by the company suggested that the area is tectonically stable and apparently has been so for several million years.

METHODS OF STUDY

A scarcity of detailed geologic information for the eastern Mojave Desert prompted the U.S. Nuclear Regulatory Commission to support the Geological Survey in the present investigation, begun in 1974, which was aimed principally at determining the recency of faulting. The Nuclear Regulatory Commission also funded a separate project by the Geological Survey to monitor the seismicity of the eastern Mojave Desert. In 1974 a number of seismic stations were installed to cover the general region between Needles, Calif., and the Imperial Valley.

Early in the studies it was apparent that the near lack of seismicity in the region was matched by a virtual absence of Quaternary surface displacement along faults. The region around the Vidal site displayed none of the features of active tectonism common to much of the rest of the Basin and Range physiographic province. To document this tentative conclusion and to provide a partial basis for understanding this unusual geologic situation, it was decided to map in detail an area centered about the Vidal site, chiefly Vidal Valley and adjoining parts of the Whipple Mountains, Riverside Mountains, and Mopah Range (fig. 1; pl. 1). Six 7½′ quadrangles and parts of four other 7½′ quadrangles were mapped in this phase of work, which was followed by reconnaissance mapping of a larger area generally surrounding the core of more detailed work.

Throughout the study, emphasis was placed on searching for evidence of youthful faulting, so that most of the effort was directed toward the stratigraphy and structure of the upper Cenozoic rocks. No detailed study was made of the pre-Tertiary, generally metamorphosed rocks, except in the Riverside Mountains, where an attempt was made to divide a sequence of probable uppermost Paleozoic and Mesozoic metamorphosed sedimentary rocks. The Paleozoic and Mesozoic rocks probably hold most of the keys to full understanding of the major structural evolution of the region, but the complex structure and metamorphism, as well as the widely scattered outcrops, make understanding of the stratigraphy very difficult and beyond the scope of the present work.

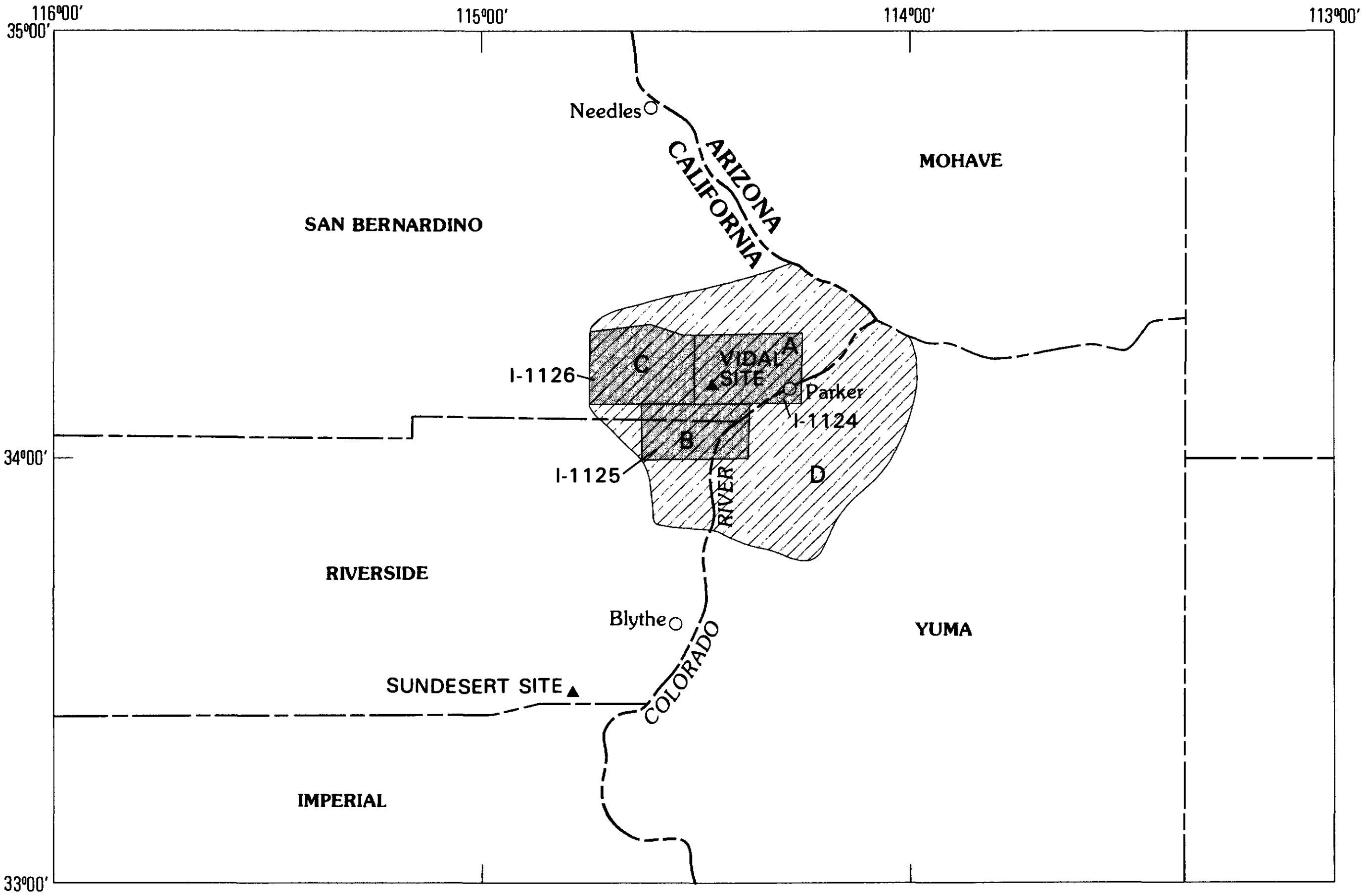


FIGURE 1.—Index map of the eastern Mojave Desert, showing location of 1:24,000 scale maps (A, B, C), Vidal-Parker region (D) mapped at 1:125,000 scale (this report), and Vidal and Sundesert former proposed nuclear power reactor sites.

Even though the Vidal site was subsequently abandoned for plant technical reasons, the region remains attractive geologically and tectonically for the siting of nuclear facilities.

The main purpose of this report is to record and, where appropriate, to interpret new geologic information gained by Geological Survey and power company investigations on behalf of the Nuclear Regulatory Commission. This report should be regarded as an attempt to synthesize, however tentatively, some fragments of the geologic history and preliminary geophysics of the eastern Mojave Desert in both California and Arizona, particularly those aspects that bear upon the structural history of the region.

It should be emphasized that the fieldwork for this report was completed in 1975, and the report itself was finished in 1977, just before a tremendous amount of new geologic information became available on the region. I have tried to include a few references on the earliest new work but have not taken into account or discussed all the implications therefrom. For further references and papers, see the report edited by Frost and Martin (1982).

ACKNOWLEDGMENTS

I am much indebted to my colleague, D. D. Dickey, who was largely responsible for painstaking mapping of most of the Quaternary deposits in the area. Even though the work was done independently, we were aided by the geologic groundwork laid down by consultants to Southern California Edison Co.; Woodward McNeil and Assoc.; and Fugro, Inc. We are particularly indebted to W. B. Bull of the University of Arizona for his fundamental stratigraphic subdivision of the Quaternary deposits.

I acknowledge with thanks the cooperation of Dr. Shawn Biehler of the University of California at Riverside in providing gravity data for part of the region. These data were substantially supplemented by further gravity observations and data reduction by

Frank E. Currey and D. L. Healey of the U.S. Geological Survey.

Several potassium-argon dates were determined by R. F. Marvin, and a fission-track age was obtained by C. W. Naeser.

Reviews of the manuscript by D. D. Dickey and K. A. Sargent of the Geological Survey were most helpful.

Several other members of the Geological Survey assisted in various ways. F. G. Poole and P. T. Hayes visited several areas of outcrop of the upper Paleozoic rocks in the region and gave suggestions concerning their stratigraphic correlation. G. O. Bachman examined and sampled some of the Quaternary deposits and gave several helpful suggestions concerning the character and origin of the caliche zones.

I thank the Colorado River Indian Tribes for permission to study the geology on their reservation.

PHYSIOGRAPHY AND THE MOJAVE-SONORAN BELT

The Vidal-Parker region (fig. 2) is part of a larger physiographic and geologic belt, which lies in the south-central part of the Basin and Range province. It is south of the predominantly linear north-trending structures of the province, southwest of the southern periphery of the Colorado Plateau province, and northeast of the northwest-trending ranges within the San Andreas and central Mojave fault system (Fenneman, 1931, pl. 1). The Vidal-Parker region is within the Sonoran Desert section of the Basin and Range province; I propose the name Mojave-Sonoran Belt (fig. 2; pl. 2) for this area as it connects or is transitional between the Sonoran Desert of southern Arizona and the Mojave Desert of southeastern California (Carr and Dickey, 1977). Aside from its geologic and geophysical characteristics, the belt is distinguished physiographically by diversely oriented ranges, most of which are less linear and have less relief than most other ranges elsewhere in the Basin and Range province. Bedrock crops out in many of the valleys, and the slopes at the foot of the mountains are widely pedimented.

The Colorado River crosses the heart of the Mojave-Sonoran Belt between the towns of Needles and Blythe, Calif. Except for contiguous drainage incision and considerable regional erosion, the physiographic effects of the river are relatively minor. The course of the Colorado River in the Vidal-Parker region was influenced by several factors, some of which will be touched upon at various points in this report. It should be noted that, whereas all of western Arizona has an integrated drainage system into the Colorado River, several areas immediately west of the river in California are closed depressions with internal drainage (Ford Dry Lake area west of Blythe and Rice Valley-Danby Lake area).

The Mojave-Sonoran Belt may be viewed as a physiographic and structural southeastward continuation of the Walker Lane Belt or structural zone of western Nevada (fig. 2). I consider the Walker Lane Belt to be a structural-physiographic zone as much as 100 km wide, rather than the narrow zone originally defined by Locke, Billingsley, and Mayo (1940). Its southwest edge is along the Fish Lake Valley–Death Valley–Furnace Creek fault zone; the northeast edge is defined physiographically by the southern termination of northerly trending basins and ranges. In much of southern Nevada this boundary is the Las Vegas Valley shear zone. Other similarities in structural style of the Walker Lane Belt and Mojave-Sonoran Belt will be brought out later.

STRATIGRAPHIC HISTORY

Rocks of the Vidal-Parker region are divisible into three general groups, partly in accordance with their involvement with a major structural feature, the Whipple Mountains detachment fault: (1) pre-Tertiary metamorphic, intrusive, and sedimentary rocks in the upper and lower plates of the fault; (2) Tertiary volcanic and sedimentary rocks older than the detachment fault and, in most areas, displaced by it; and (3) Tertiary and Quaternary volcanic and sedimentary rocks deposited after movement of the fault. Except for a few details that bear specifically upon the structural history, only general characteristics of the rocks are described here. For details of individual map units, the reader is referred to geologic maps of the area at 1:24,000 scale (Carr and others, 1980; Carr and Dickey, 1980; and Dickey and others, 1980).

METAMORPHIC, INTRUSIVE, AND SEDIMENTARY ROCKS

MESOZOIC, PALEOZOIC, AND OLDER(?) ROCKS

These units form the resistant cores of most of the mountain ranges of the region, but their structural and stratigraphic sequence is complex and not well understood. I believe that many rocks of this group, shown as Precambrian on local and regional geologic maps, are Paleozoic or younger in age.

ROCKS AT THE EAST FOOT OF THE RIVERSIDE MOUNTAINS

Within the mapped area (pl. 1), some of the oldest and structurally lowest rocks (lp, pl. 1) lie at the east foot

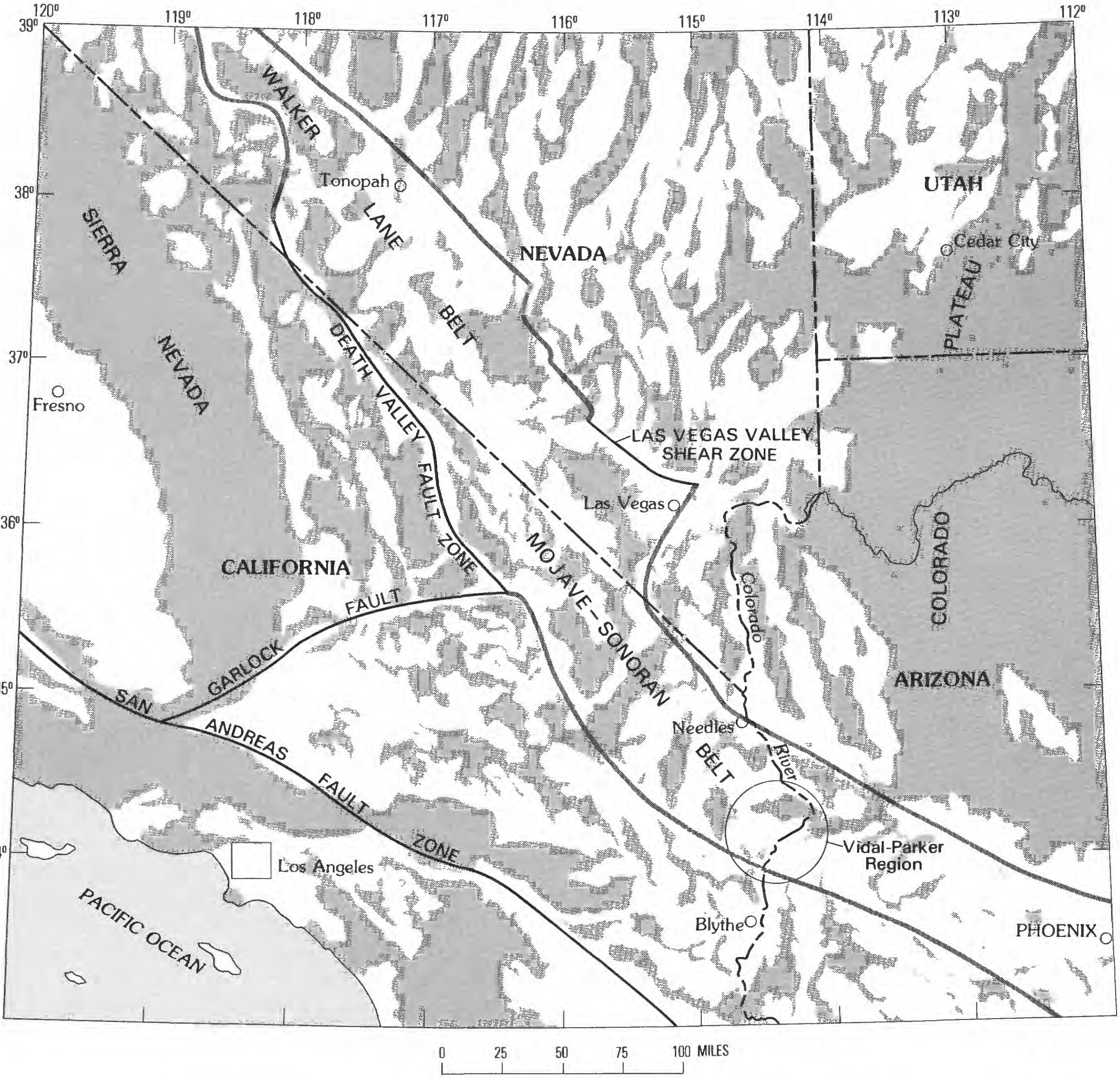


FIGURE 2.—Basins and ranges of Arizona, Utah, Nevada, and southeastern California showing the location of the Vidal-Parker region, Walker Lane and Mojave-Sonoran Belt, and San Andreas fault zone. White areas are basins; dark areas are ranges.

of the Riverside Mountains, where they are overlain in low-angle fault contact by a sequence of partly metamorphosed sediments of late Paleozoic and Mesozoic(?) age. The unit consists largely of gneiss and migmatite of highly variable composition. The polymetamorphic character and structurally low position strongly suggest a Precambrian age, but no normal depositional contact of lower Paleozoic beds on this sequence was observed, even though W. B. Hamilton (written commun., 1974) reported a depositional contact to the south in the Big Maria Mountains.

ROCKS OF PROBABLE LATE PALEOZOIC AGE

Sedimentary rocks, mostly of late Paleozoic age (units lz1, lz2, uz1, uz2, and uz, pl. 1), are recognized in the lower plate of the Whipple Mountains detachment fault in the Riverside and Big Maria Mountains, Calif., and in the upper plate of that fault in the Buckskin Mountains, Ariz. One of the best exposed and least metamorphosed sections of this sequence, however, occurs outside the geologically mapped area of plate 1 in the Arica Mountains, a small range about 15 km southwest of Rice, Calif. (See unit Pz, pl. 2.) Metamorphism has destroyed virtually all fossils except for a few crinoid stems seen in rocks in the Riverside Mountains. The section commonly rests structurally on gneissic rocks, which are probably Precambrian in some areas. Low-angle faulting, resulting in both attenuation and repetition, makes mapping of individual units very difficult. In general, however, the section consists of three main parts, a lower rather thin-bedded carbonate and shaly zone, a middle quartzite sequence, and an upper fairly massive limestone and dolomite sequence. Were it not for the presence of the quartzite, which is distinctive, identification of this group of rocks would be difficult. The quartzite is thin bedded, fine grained, and quite uniform. It lacks prominent crossbedding and is distinctly finer grained than typical Coconino Sandstone.

The quartzite of the Vidal-Parker region is tentatively correlated with the Queantoweap Sandstone of McNair (1951) or the Esplanade Sandstone of the Supai Group (McKee, 1975) in northwestern Arizona. Above the quartzite, limestone and dolomite beds contain local quartz sand zones overlain by more massive limestone and dolomite that are probably generally correlative with the Kaibab Limestone of northwestern Arizona. The sandy zones may be stratigraphically equivalent to the Coconino Sandstone. Keith Howard (written commun., 1979) of the U.S. Geological Survey believes that the quartzite in the Arica Mountains, as well as similar rocks in the Kilbeck Hills and Little Piute Mountains (pl. 2), is Coconino, even though the quartzite lacks crossbedding.

More typical Coconino occurs in the Plomosa (Miller and McKee, 1971) and Harquahala Mountains of Arizona and in the southern Big Maria Mountains, Calif. (W. B. Hamilton, written commun., 1974; fig. 3). I visited the last two localities in company with F. G. Poole, P. T. Hayes, and D. D. Dickey of the Geological Survey, and all agreed that quartzites typical of the Coconino are present. It was also concluded that the quartzite of the Arica, Riverside, and Buckskin Mountains is not typical of the Coconino; hence, the tentative correlation of the quartzite with the Esplanade or Queantoweap Sandstones. In my opinion, quartzite in Miller and McKee's (1971) deformed section in the Plomosa Mountains resembles the Esplanade Sandstone, not the Coconino Sandstone. At the southern Big Maria Mountains section, two arenaceous formations are present. The lower, correlated by W. B. Hamilton (written commun., 1974) with the Supai Group, is alternating brown sandstone and gray silty and sandy carbonate rock. This unit has a soft slope at the top that is somewhat loosely cemented gypsiferous sandstone. Above it is typical Coconino, a fairly pure quartzite with large crossbeds. This section of Pennsylvanian-Permian rocks in the southern Big Maria Mountains is quite different from rocks of the same probable age in the Riverside Mountains only 40 km to the north, or in the Arica and Buckskin Mountains to the northwest and northeast; none of these localities, a short distance to the north of the Big Maria and Plomosa Mountains, exhibit any typical Coconino Sandstone. Structural thinning of the sections has probably occurred in some areas, but the difference in quartzite lithology in the northern versus the southern sections appears to be real.

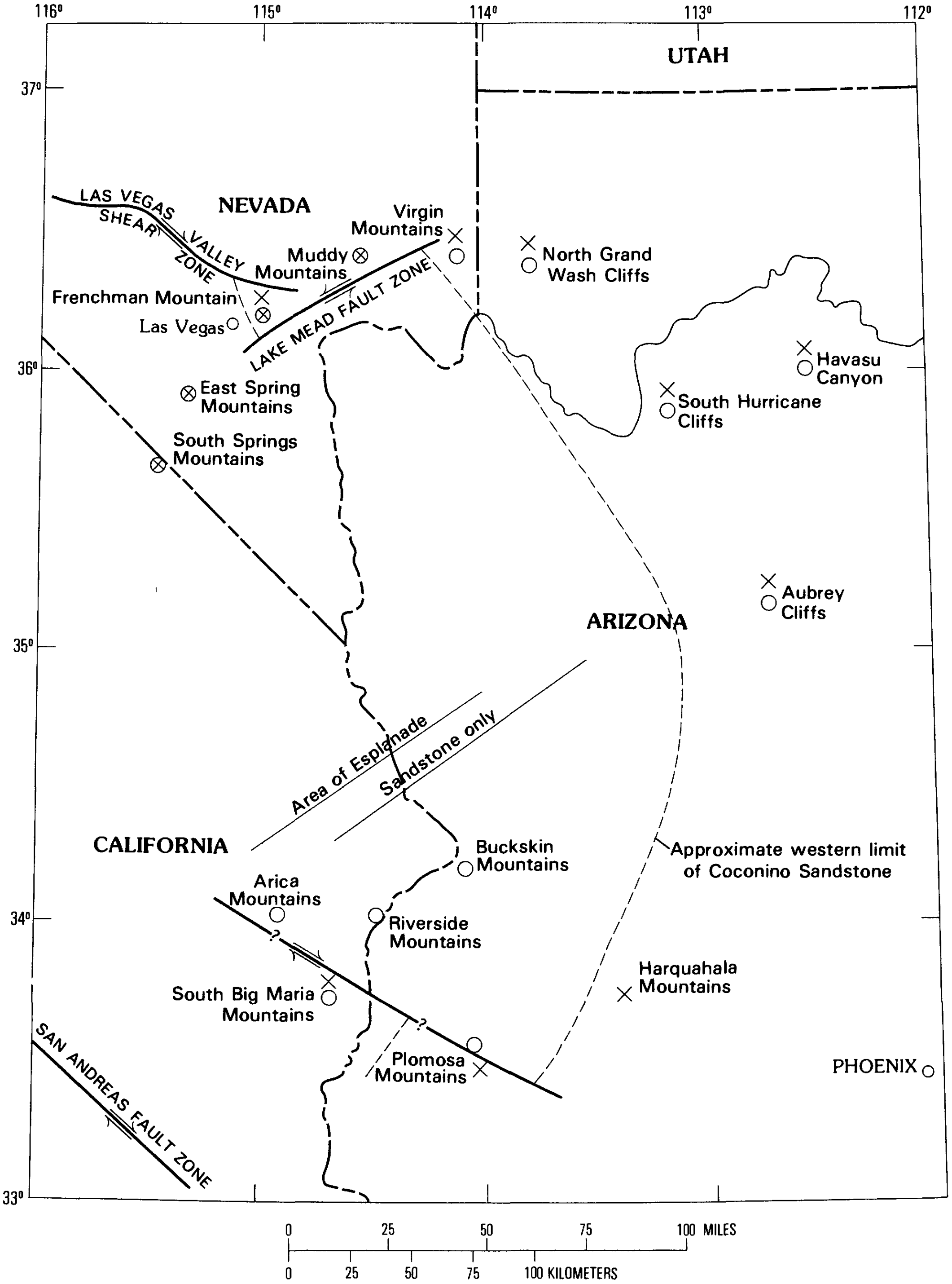
Above the sandstone or quartzite interval in all the sections is a sequence of relatively pure but locally cherty massive limestone, dolomite, or marble which corresponds in a general way with the Permian Kaibab Limestone. More carbonate rocks, possibly of Mesozoic age, are present locally above the Kaibab-type limestones. In several areas these units are overlain by strongly foliated banded gneisses.

POSSIBLE STRUCTURAL SIGNIFICANCE OF CHANGES IN CHARACTER IN THE UPPER PALEOZOIC ROCKS

The abrupt change of the Pennsylvanian-Permian section between the Big Maria and Riverside Mountains, and in a short distance within the Plomosa Mountains, and the regional pattern of distribution of these rocks to the north (fig. 3) strongly suggest structural displacement. Miller and McKee (1971) cited thrusting to explain the dissimilar sections in the Plomosa Mountains. Assuming northerly facies trends, the absence of Coconino-like lithology in the Arica, Riverside, Buckskin, and part of the Plomosa Mountains suggests that strike-slip faulting as well as thrusting may be responsible. Longwell, Pampeyan, Bowyer, and Roberts (1965, p. 36) pointed out the anomalous presence of Coconino Sandstone at Frenchman Mountain near Las Vegas, and R. G. Bohannon and R. E. Anderson (oral commun., 1978) believe that its presence there is due to westward shift on a major zone of strike-slip faults (fig. 3).

LOWER PLATE GNEISSES

The most extensively exposed pre-Tertiary rock in the Vidal-Parker region is fairly uniform, finely banded, or foliated feldspathic gneiss (lower plate gneisses, unit lg, pl. 1) that makes up the cores of several of the mountain ranges in the region. It is more than 500 m thick in the Whipple Mountains. Much of the unit is mylonitic and superficially resembles metamorphosed flow-banded lava, but in many areas it consists of a smeared and metamorphosed granitic complex. Some of these rocks in the Whipple Mountains were placed in the amphibolite facies grade of metamorphism by Terry (1972).



EXPLANATION

× COCONINO SANDSTONE

○ ESPLANADE SANDSTONE (Queantoweop Sandstone of McNair, 1951)

⊗ PERMIAN ROCKS—Coconino or Esplanade Sandstone not separated

⇌——?— FAULT OR FAULT ZONE—Arrows show direction of movement; queried where uncertain

Figure 3.—Postulated areal distribution of Permian rocks at localities in western Arizona, southern Nevada, and southeastern California.

Augen gneiss, quartzite, and marble of late Paleozoic or Mesozoic(?) age are included in the lower part of the unit in some areas. In the Vidal-Parker region, the well-banded or laminated gneiss occurs only in the lower plate of the Whipple Mountains detachment fault. Davis, Anderson, Frost, and Shackelford (1980) and Anderson, Davis, and Frost (1979) described these rocks in the Whipple Mountains in some detail. These authors pointed out that the mylonitic zone or "carapace" of metamorphism cuts across these gneissic lower plate rocks.

The age, structural history, and thermal history of the banded gneiss and lower plate rocks in general are not precisely known. A K-Ar (potassium-argon) date of 46.7±1.1 m.y. (million years) (R. F. Marvin, written commun., 1976) was obtained on feldspar from augen gneiss near the base of the unit in the northeastern part of the Riverside Mountains. Zircon from the same sample yielded a fission-track age of 62.1±3.7 m.y. (C. W. Naeser, written commun., 1977). These ages must be considered as only approximate minimums, but they follow rather closely the end of major Mesozoic-early Cenozoic plutonic activity in southern Arizona and southeastern California (Armstrong and Suppe, 1973). Support for a general correlation between the dated rock in the lower plate of the Whipple Mountains detachment fault in the Riverside Mountains and similar rocks in the lower plate in the northeastern Whipple Mountains is found in a K-Ar date on hornblende reported by Terry (1972) of 41.5±3 m.y. However, several nearly concordant fission-track ages of about 19 m.y. were reported by Dokka and Lingrey (1979) from lower plate gneisses in the eastern Whipple Mountains.

Metamorphic rocks of this general type have been called Precambrian by previous workers (W. B. Hamilton, written commun., 1974; Bishop, 1963; Wilson and others, 1969) in the Vidal-Parker region. Several factors suggest that most of these rocks may not be Precambrian, but Mesozoic in age. In two places in the mapped area, gneisses with dolomite or marble and quartzite intercalated near the lower contact overlie sedimentary rocks of probable late Paleozoic age. In the Riverside Mountains this carbonate rock-quartzite-gneiss sequence occurs in the lower plate of the Whipple Mountains fault; in the western Buckskin Mountains northeast of Parker, a very similar sequence of upper Paleozoic rocks is overlain by gneissic granite in the upper plate of that fault. In the Big Maria Mountains, W. B. Hamilton (written commun., 1974) mapped rocks of this general type, which he called "Mesozoic greenschist" or metavolcanic and metasedimentary rock, as structurally overlying the upper Paleozoic section. At most localities these probable Mesozoic rocks have been mapped with low-angle faults separating them from the underlying Paleozoic units, but the fact that similar marble beds occur near this contact at several widely separated places suggests that the faulting is not major. Relationships with subjacent upper Paleozoic and lower Mesozoic(?) sedimentary rocks suggest that the banded gneiss may be the thick smeared-out margin of a large semiconcordant pluton. The mylonitic gneiss is best developed in the range core relatively near the Whipple Mountains detachment fault of Miocene age, implying a relationship between the gneiss and fault. However, the discordance between the mylonite and other rocks of the lower plate suggests separate tectonic episodes.

MESOZOIC(?) ROCKS

A separate group of rocks (unit lx, pl. 1), found only in the southeastern Riverside Mountains in the Vidal-Parker region, is also believed to be Mesozoic (Hamilton, 1964) in age, but these rocks are somewhat different from other probable Mesozoic sections in the region. The rocks consist of mostly low-grade metasediments including sandstone, minor amounts of conglomerate, marble and dolomite with phyllite, greenschist, and one interval of probable metatuff. Lower Triassic rocks generally similar in description to the southeast Riverside Mountains sequence have been reported in the Providence Mountains about 140 km to the northwest (Hazzard and others, 1938). Pelka (1973, p. 35) has pointed out the vague similarity between Mesozoic(?) rocks of the Big Maria and Riverside Mountains and his Palen formation of probable Triassic age in the northern Palen Mountains about 50 km to the southwest, which Pelka has called the Palen Formation for those mountains. I was impressed, however, by the differences in character of these rocks, particularly between those of the Riverside and Palen Mountains.

GRANITE GNEISS

Gneissic rocks (unit ug, pl. 1), making up part of the upper plate of the Whipple Mountains detachment fault, crop out on the flanks of the Whipple, Buckskin, and Riverside Mountains. Although locally variable, these rocks tend to be granitic in texture and composition and appear to grade laterally into gneissic granite in several areas. Dark pyroxene- and sphene-bearing phases of the unit are present locally. These rocks are generally much broken by structural movements within the upper plate of the Whipple Mountains detachment fault. Some of the gneiss is locally incorporated as breccia and megabreccia within the Tertiary section; in some areas blocks are so large that determination of such reworking is difficult.

The age of the upper plate gneissic rocks has not been definitely determined, but dates on the granitic rocks (unit Kgg, pl. 1) into which the gneisses appear to grade suggest that much of the gneiss is Mesozoic, probably Cretaceous, in age.

METAMORPHIC ROCKS INTRUDED BY DIKES AND SILLS

Another unit (mr, pl. 1), shown separately on the geologic map, occurs in the metamorphic rocks of the lower plate in the western Whipple Mountains. An area of similar rock, not separately mapped, occurs in lower plate gneisses farther east, between Savahia Peak and Chambers Well. The map unit consists of gneiss and schist intruded by swarms of dikes and sills of rhyodacite or diorite. Much of the intrusive rock is hydrothermally altered, and determination of texture and mineralogy is difficult. It cannot be ruled out that these intrusives are Tertiary in age, and, indeed, they occur only a few kilometers east of a large area of Tertiary rhyolite and rhyodacite lavas. However, field relations suggest that the unit is cut by granitic intrusive rocks, which elsewhere are mostly late Mesozoic in age.

GRANITE AND GNEISSIC GRANITE

Granites and gneissic granites (units Kg and Kgg, pl. 1) do not make up a large volume of the rocks in the mapped area, except in the West Riverside Mountains (pl. 1). Scattered smaller areas of granitic rocks occur around the periphery of the Whipple Mountains, in the Riverside Mountains, and in the vicinity of Moon Mountain 35 km south of Parker. Medium- to coarse-grained granite and quartz monzonite are the most common rock types. As mentioned previously, the granites typically grade into gneissic granite of similar composition. In most areas, as in the West Riverside Mountains, the gradation is fairly abrupt.

Several K-Ar dates on granitic rocks have been obtained on biotite and feldspar from scattered localities in the mapped area and are listed in table 1.

Except for the date of 146 m.y. on hornblende reported by Terry (1972) from the northeastern part of the Whipple Mountains, these dates from the Riverside, Turtle, and southern Whipple Mountains agree quite well. The close agreement in age between the samples from the West Riverside Mountains and those from the southern Turtle Mountains suggest that these granites are parts of the same plutonic episode, even though the rocks in the Turtle and Riverside Mountains are somewhat different mineralogically.

Two other K-Ar dates on granite outside the Vidal-Parker area were obtained by consultants to San Diego Gas and Electric Co. (1976, v. 2, fig. 2.5-28). These dates from the northeastern Mule Mountains southwest of Blythe are 96.0±3.6 and 89.4±3.3 m.y.

TABLE 1.—*Potassium-argon dates on granitic rocks in Vidal-Parker region*

Sample	Location	Date and error (million years)	Reference
---	West Riverside Mts.	98.5±4.0	Bishop (1963).
SC-69-62	Do.	92.8±1.9	Armstrong and Suppe, (1973).
SC-69-63	Turtle Mts., eastern	95.6±1.9	
SC-69-64	Do.	93.6±1.9	
MWC-39-74	Whipple Mts., southern		
biotite		87.9±2.1	This report.[1]
orthoclase.		90.7±1.4	
KA 700	Whipple Mts., northeastern	146±10	Terry (1972).
KA 704	Whipple Mts., southeastern	81±2	
---	Chemehuevi Mts.	60	R. E. Anderson (U.S. Geological Survey, oral commun., 1975).

[1] U.S. Geological Survey K-Ar ages given in this report have been corrected for new constants.

All the above dates agree well with those on maps of dated Mesozoic and early Tertiary igneous rocks in southwestern United States prepared by Armstrong and Suppe (1973). It would appear, however, that the new dates serve to strengthen a pattern of northwest-trending age (or metamorphic) belts of plutons in the Mojave Desert region. These belts seem to crosscut the boundary of the area of large volumes of granite (as outlined by Armstrong and Suppe, 1973), and they may persist southeastward into the region of the Colorado River where granitic bodies are fairly numerous but smaller in volume.

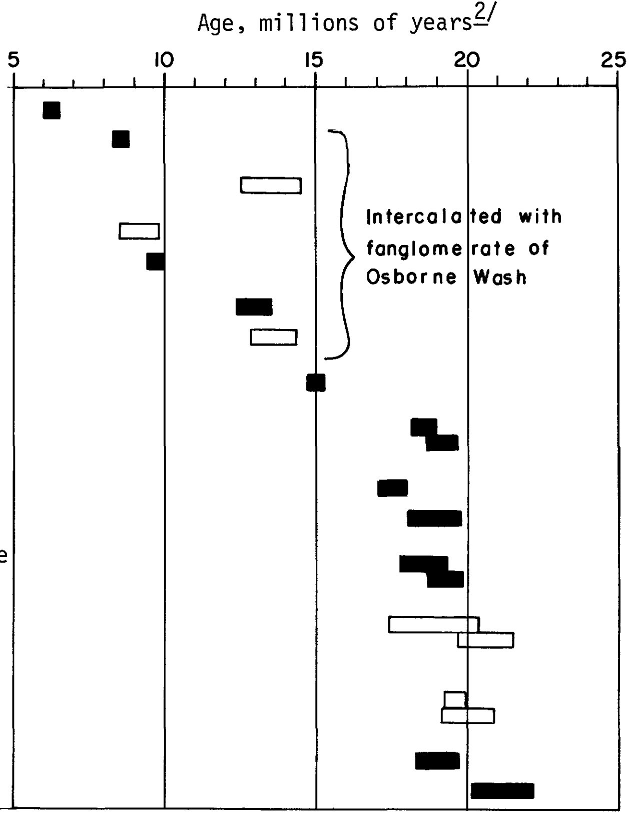
TERTIARY VOLCANIC AND SEDIMENTARY ROCKS

Rocks of Tertiary age in the Vidal-Parker region are Miocene and Pliocene, but all the volcanic rocks of significant volume are Miocene (table 2). Several K-Ar dates support this conclusion, as will be discussed later.

Except possibly in the Mopah Range, the preserved sequences of Tertiary rocks are normally less than about 1,000 m thick, but they are characterized by abrupt changes in thickness and lithology. These are illustrated in figure 4, which shows a general stratigraphic sequence for each of five areas. With the exception of a few discontinuous key units, correlations between parts of the section are equivocal, owing to complex structure, unconformities, and lateral changes. One cannot normally find the exact section depicted in figure 4 at any single locality. However, despite the variability, certain general features of the section can be recognized in most areas.

TABLE 2.—*Age of Tertiary volcanic rocks in Vidal-Parker region*

Sample number[1]	Rock type, name or locality
MWC-72-74	Andesite of West Portal
MWC-55-74	Andesite of Osborne Wash
F-1	Andesite of Osborne Wash
RD-16	Basalt, Buckskin Mountains
YU-179-PW	Basalt, Buckskin Mountains
MWC-56-74	Basalt of Lake Moovalya
RD-21	Basalt, Black Peak
MWC-31-76	Basalt of the Mopah Range
MWC-79-74	Peach Springs Tuff { sanidine biotite
MWC-30-76	Andesite of Vidal
V-1	Andesite of Vidal
MQ-4	Rhyolite lava, Mopah Range { hornblende biotite
C-597 C-598 } [3]	Andesite, south end Turtle Mountains
C-599 C-600 } [3]	Andesite, south end Turtle Mountains
FK-1	Andesite, South Whipple Mountains
FK-2	Andesite, South Whipple Mountains



[1] Samples arranged in probable stratigraphic order.
Data sources:
MWC and MQ: Marvin, R. F., and Dobson, S. W., 1979, Radiometric ages: Compilation B, U.S. Geol. Survey: Isochron/West, no. 26, p. 6 and 10-11. (Note: Above reference erroneously places determination no. 66 (p. 10) for MWC-31-76 directly beneath Peach Springs Tuff. This sample is from basalt of the Mopah Range, which directly overlies the Peach Springs; hence, age is not unreasonable.) Dickey, D. D., and others, 1980, Geologic map of the Parker N.W., Parker, and parts of the Whipple Mountains S.W. and Whipple Wash quadrangles, California and Arizona: U.S. Geol. Survey Map I-1124; Carr, W. J., and others, 1980, Geologic map of the Vidal N.W., Vidal Junction and parts of the Savahia Peak S.W. and Savahia quadrangles, California: U.S. Geol. Survey Map I-1126.
F-1, V-1, FK-1, FK-2, C-597, -598, -599, -600: Information concerning site characteristics, Vidal nuclear generating station, Southern California Edison Co., 1974, v. II, sec. 2.5, p. 36-37.
RD-16, RD-21: Early site review report, Sundesert nuclear plant, San Diego Gas and Electric Co., 1976, Amendment 10, figs. 2.5-28.
YU-179-PW: Armstrong, R. L., and others, 1976, K-Ar dates from Arizona, Montana, Nevada, Utah, and Wyoming: Isochron/West, no. 16, p. 4.

[2] Solid bar represents a date considered reasonable, and a sample whose stratigraphic position is known; open bar, a sample whose age may be spurious or whose stratigraphic position is uncertain.

[3] Two samples from the same locality.

Virtually no detailed work had been published on the Tertiary rocks of the Vidal-Parker region prior to our field studies (Carr and others, 1980; Dickey and others, 1980; Carr and Dickey, 1980). F. L. Ransome briefly described the stratigraphy in the southeastern Whipple Mountains in an unpublished work which was done on behalf of the Metropolitan Water District of Southern California in the early 1930's. He applied, informally, the names Gene Wash and Copper Basin to formations of Tertiary rocks along the route of the aqueduct through the Whipple Mountains. His reports are in the files of the Metropolitan Water District of Southern

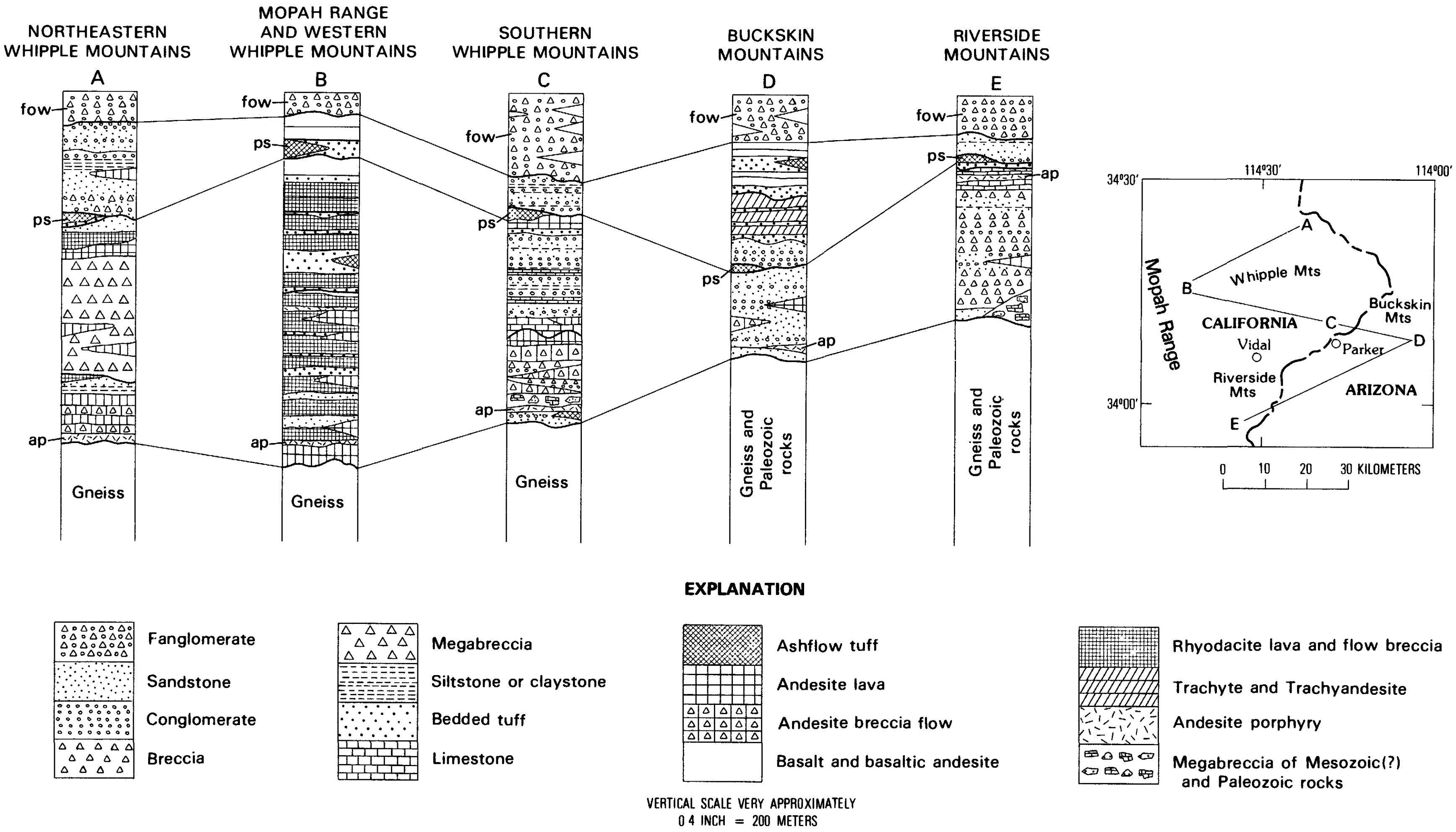


FIGURE 4.—Composite diagrammatic columnar sections of Tertiary rocks in the Vidal-Parker region (Bouse Formation omitted). Heavy wavy lines, unconformities. Three key units allow correlations between parts of the section: Peach Springs Tuff (ps), fanglomerate of Osborne Wash (fow), and andesite porphyry (ap).

California. Kemnitzer (1937) used these names in his structural study of the Whipple Mountains. Because of the abrupt stratigraphic changes in the region, these names are not used in the present work.

VOLCANIC ROCKS

Lava flows and associated tuffs and breccias make up the majority of the Tertiary section only in the Mopah Range and western Whipple Mountains, and in a small group of hills in Chemehuevi Valley west of Lake Havasu City (pl. 1). Compositionally, they range from rhyolite to basalt, but most of the rocks are rhyodacitic to andesitic. Nearly all the volcanic rocks lack, or have only very minor amounts, of phenocrystic quartz. A few partial chemical analyses, representative of the major rock types, are given on the geologic quadrangle maps (Dickey and others, 1980; Carr and others, 1980).

ANDESITE LAVAS

In general the oldest volcanic rocks are andesites, although in the western Whipple Mountains and Mopah Range, andesites are intercalated with rhyodacite lavas. Andesite lavas and breccia flows are prominent around the periphery of the Whipple Mountains, reaching their greatest volume in the southeastern Whipple Mountains where they commonly intertongue with reddish-brown granite gneiss breccia and arkosic conglomerate and sandstone. Dikes of altered andesite are present in the pre-Tertiary upper plate basement rock of the eastern Whipple Mountains, and, together with the distribution of the lava, point to that general area as the source. However, as discussed later, the upper plate rocks are allochthonous and have probably been transported many kilometers in a northeasterly direction with respect to the lower plate. Characteristically, the dark fine-grained lavas in the Whipple Mountains are breccia flows—used here to mean lava breccia consisting entirely of fragments enclosed in a lava matrix of the same material. That these are not tectonic or landslide breccias is indicated by the fact that they contain or are locally in depositional contact with sedimentary rocks that are undisturbed. Breccia of this type has been described in the Cane Spring quadrangle in Nevada (Poole and others, 1965). Zeolites and calcite are characteristic alteration products, and copper carbonate stains are seen commonly on fracture surfaces.

A particularly distinctive unit, an andesite porphyry, is locally present in many areas, generally near the base or in the lower part of the Tertiary section. It is typically a dark-purplish-gray rock crowded with flow-alined plagioclase laths as much as 2 cm long—a kind of coarse trachytic texture. It displays both extrusive and intrusive relations and occurs in scattered small areas throughout the Vidal-Parker region. If all the occurrences are the same age, the porphyry records a widespread synchronous magmatic event.

RHYODACITE LAVAS

Rhyodacite lavas and flow breccias make up the bulk of the Mopah Range and are present in the western Whipple Mountains and hills in Chemehuevi Valley. In the southern Mopah Range, eight separate flows were mapped (Carr and others, 1980). Many of these cannot be easily identified separately in the field, and in the western Whipple Mountains where the lavas are extensively altered and faulted they were not mapped separately. At least one flow is a rhyolite. None of the flows contain sanidine feldspar phenocrysts, and sparse quartz occurs only in the rhyolites. The oldest units contain prominent biotite and hornblende; the youngest contain clinopyroxene and orthopyroxene as the predominant mafic minerals.

Thick flow breccias, thin air-fall tuffs, and one nonwelded ash-flow tuff are associated with the lavas. Several plug domes are present which probably served as feeders for some of the flows. The location of these plugs and the general characteristics and distribution of the lavas and tuffs, together with a distinct gravity low (pl. 2) just east of the Mopah Range, suggest that area is the eruptive center.

Rhyodacites interfinger with andesites in the western Whipple Mountains west of Savahia Peak. Unfortunately, individual flows could not be mapped or correlated directly with andesites to the east or rhyodacites to the west. It is reasonable, however, on the basis of field relations, isotopic dates, and general lithology, to conclude that the andesite of the Whipple Mountains and rhyodacite lavas of the Mopah Range are at least partly contemporaneous.

Dates were obtained on biotite and hornblende from a rhyolite flow near the southern end of the Mopah Range. The rock is a vitrophyre at the base of a flow near the middle of the exposed sequence. Biotite gave an age of 18.9±0.5 m.y., and hornblende, 18.2±0.8 m.y. (R. F. Marvin, written commun., 1976). On the basis of this date and field relations, an age of about 27 m.y., obtained by consultants to Southern California Edison Co. (Information Concerning Site Characteristics, Vidal Nuclear Generating Site, v. 2, table 2.5-2) on a flow stratigraphically higher in the sequence, appears to be erroneous.

BASALTIC ROCKS

Basalt and basaltic andesite are prominent in the upper part of the volcanic sequence. These flows appear to have originated from two separate areas—the Mopah Range and the Buckskin Mountains. Exact source areas in the Mopah Range have not been identified. Basalt crops out near the center of Vidal Valley (pl. 1) and extends in a belt about 70 km northwestward to the Stepladder Mountains (pl. 2). In the Mopah Range area, a variety of mafic rocks are mapped in this group, including a few dark trachyandesites. Several thin scoriaceous basalt flows are intercalated with the rhyodacite lava flows; most of these basalt flows contain olivine, and one is characterized by a lack of clinopyroxene. Basalts generally younger than the rhyodacite lavas include the basalt near Vidal, which contains rare olivine and a few quartz xenocrysts, and another flow possibly related to the basalt near Vidal, which contains both clinopyroxene and orthopyroxene and lacks olivine. The most widely exposed series of basalts in the Mopah Range area that overlie the rhyodacite lava pile, are also probably younger than the Peach Springs Tuff. They are typical olivine basalts.

Most, if not all, of the basaltic rocks of the Buckskin Mountains and southern Whipple Mountains area (fig. 4) are intercalated in the fanglomerate of Osborne Wash; they are shown separately (pl. 1) only where they are fairly thick and continuous. These basalts are distributed in a poorly defined belt from the Cactus Plain southeast of Parker northward through the Buckskin Mountains and across the Bill Williams River as far as the south edge of Dutch Flat (pl. 2). The presence of pyroclastic deposits and feeder dikes indicates that the vent area for most of these flows lies in the Buckskin Mountains near the head of Giers Wash, about 20 km northeast of Parker.

Basalts of the Buckskin Mountains area are also variable in composition and mineralogy. One of the distinctive flows, called the basalt of Lake Moovalya (Dickey and others, 1980), is recognized only in the area northeast of Parker, but similar rocks are mentioned by Suneson and Lucchitta (1978) in the area northeast of the Bill Williams River. The rock is a porphyritic olivine basalt containing conspicuous megacrysts of plagioclase and olivine as much as 1.5 cm across.

Younger flows in the group tend to be less mafic; some are basaltic andesite and a few may best be called trachybasalts. Commonly, they are diabasic in texture with small olivine phenocrysts. One of the youngest flows, the andesite of West Portal (Dickey and others, 1980), occurs in a small area north of Parker on the flanks of the Whipple Mountains. It is characterized by rare corroded quartz xenocrysts with clinopyroxene coronas, indicating a stage of disequilibrium in the crystallization history of the rock.

Several dates are available for basalts of the Vidal-Parker region (table 2). A few additional dates have been reported (Damon, 1970, p. 40; Eberly and Stanley, 1978; E. G. Frost, San Diego State University, written commun., 1960), but they are omitted here because they appear too old based on present field knowledge. Even so, it is obvious that basaltic volcanism in the region continued sporadically for a long time—at least 10 m.y. Most of the dated basalts are intercalated in the fanglomerate of Osborne Wash, near the edges of the basaltic eruptive center in the Buckskin Mountains, which indicates an equally long period of time for accumulation of that generally coarse detrital deposit.

The youngest dated basaltic rock is the previously mentioned andesite of West Portal, a relatively insignificant unit dated at about 6 m.y. (table 2). The only other younger basalt occurs on the Cactus Plain, 22 km southeast of Parker, where a slightly eroded undated basaltic cinder cone occurs in a sand dune area.

TRACHYTIC ROCKS IN THE BUCKSKIN MOUNTAINS

During reconnaissance mapping of the Buckskin Mountains east of Parker, an interesting group of lavas was found unconformably underlying basalts of the fanglomerate of Osborne Wash (sec. D, fig. 4). Although chemical analyses are not available, petrographic examination revealed that these rocks are trachytes and trachyandesites with peralkaline affinities. They contain phenocrysts of alkali feldspar in a groundmass of glass or microlites of sodic plagioclase. Most flows examined contained a few phenocrysts of iron-rich olivine, and iron- and soda-rich clinopyroxene, probably acmite or aegerine. No biotite or phenocrystic quartz is present.

Age of these trachytic lavas is not precisely established, but because they directly underlie basalts in the fanglomerate of Osborne Wash, it is likely that they are older than about 13 m.y.; their freshness and general appearance suggest that they are probably not much older than the basalts of Osborne Wash. An age of about 14 m.y. is suggested, which is very nearly the same as the age of two major centers that erupted peralkaline rocks in the southern Great Basin (Noble, 1968; Noble and others, 1968).

PEACH SPRINGS TUFF OF YOUNG AND BRENNAN (1974)

An important marker unit in the Tertiary of the Vidal-Parker region is the Peach Springs Tuff. This ash-flow tuff is widely distributed across the margin of the Colorado Plateau in northwestern Arizona (Young and Brennan, 1974; Lucchitta, 1972). It was recognized in the Vidal-Parker region during the present field studies. The known distribution of the Peach Springs Tuff (fig. 5)

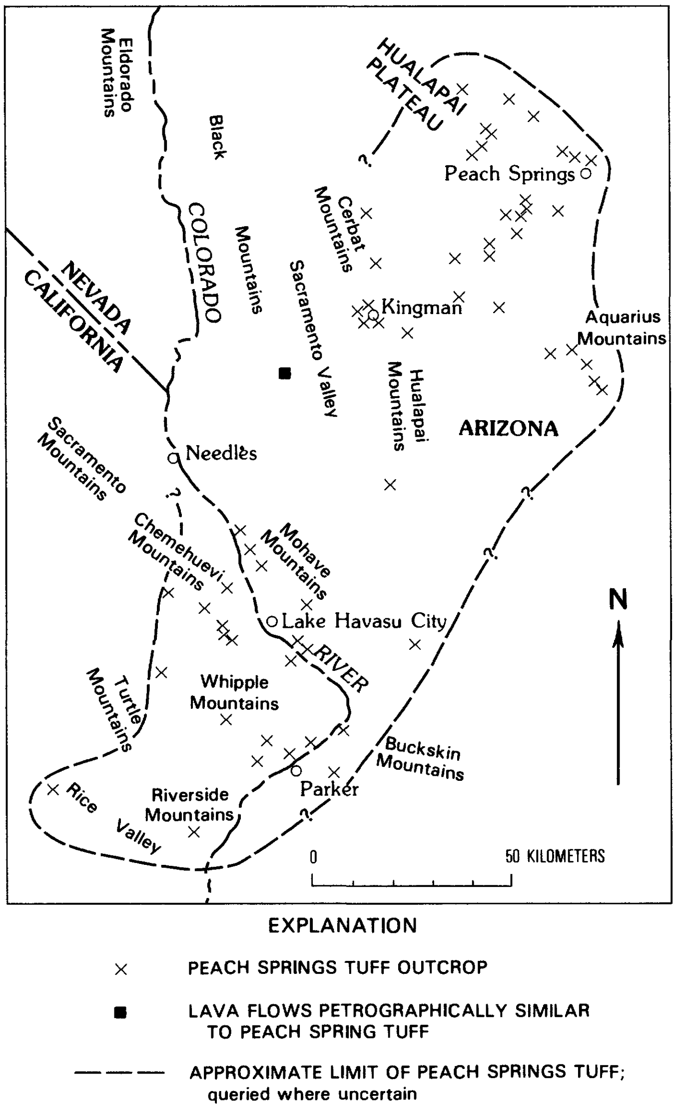


FIGURE 5.—Distribution of the Peach Springs Tuff of Young and Brennan (1974). Data in northeastern two-thirds of area from Young and Brennan (1974) and Ivo Lucchitta, U.S. Geological Survey (oral commun., 1977).

shows an elongate pattern trending northeast more than 200 km from Rice Valley in California to the Hualapai Plateau in Arizona. The exposure localities shown in figure 5 are generally quite small and irregularly distributed and probably do not adequately represent the tuff distribution in the center of the belt, particularly in the area between Needles and the Hualapai Mountains. Anderson, Longwell, Armstrong, and Marvin (1972) dated an ash-flow tuff in the Patsy Mine Volcanics of the north-central Black Mountains (fig. 5). This tuff gave widely divergent ages from 18.6 m.y. on the whole rock to as much as 40.8 m.y. on biotite. Anderson suggested that the younger age is more reasonable, and Young and Brennan (1974) mention this tuff as a possible correlative of the Peach Springs. I examined thin sections of ash-flow tuff in the Patsy Mine Volcanics collected by R. E. Anderson and found them similar petrographically to the Peach Springs. It appears likely, but not certain, that the ash-flow tuff in the Patsy Mine Volcanics of the northern Black Mountains of Arizona and Eldorado Mountains in Nevada is the Peach Springs.

Peach Springs Tuff apparently does not extend west of Needles into the northern Sacramento Mountains area. I examined ash-flow tuffs cropping out in the north-central Sacramento Mountains and they are not Peach Springs.

The distribution and thickness of the Peach Springs and other volcanics, and the presence of lava flows petrographically similar to the Peach Springs in the southeastern Black Mountains point to that general area as the probable source (fig. 5). Young and Brennan (1974, p. 84) suggested a source in the same region. No caldera has been recognized, but if one is present, it may be partly or entirely buried beneath the alluvium of Sacramento Valley. In the Vidal-Parker region the tuff is thin and very sporadically preserved, but it is present in scattered locations throughout most of the region (fig. 5; pl. 1). It commonly occurs at or near the top of the most structurally disturbed section but is locally faulted on a small scale. At most localities, sedimentary rocks appear to overlie the Peach Springs with minor disconformity.

The Peach Springs is nonwelded to moderately welded in the Vidal-Parker area and is characterized by pervasive vapor-phase alteration. However, at localities in Rice Valley near the probable distal edge, it is nonwelded, mostly vitric, and shardy. Petrographically, the Peach Springs Tuff of the Vidal-Parker region appears to be almost identical to the Peach Springs Tuff of the type area in northwestern Arizona. (See table 3.) Quartz appears to be rarer in the tuff in the Vidal-Parker region—quartz is absent in some samples. Plagioclase is somewhat variable in amount in the Vidal-Parker samples. However, the large size (1–3 mm) of the sanidine phenocrysts is characteristic of Peach Springs Tuff from both areas.

Peach Springs Tuff from a locality near Parker was dated by K-Ar at 19.2±0.5 m.y. on biotite and 18.6±0.4 m.y. on sanidine[1] (Marvin and Dobson, 1979, p. 10). Whole-rock ages on basalt directly underlying and overlying the tuff at another locality between the Mopah Range and Whipple Mountains gave ages of 17.4±0.4 m.y. and 14.9±0.3 m.y., respectively. Dates reported

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[1] U.S. Geological Survey K-Ar ages given in this report have been corrected for new constants.

TABLE 3.—*Petrographic comparison of the phenocrysts of Peach Springs Tuff of the Vidal-Parker region with those of the type area in northwestern Arizona*

	Average percent	
	Vidal-Parker region[1]	NW. Arizona[2]
Phenocrysts	5-15	4-14
Sanidine	76.0	74.0
Oligoclase	16.0	18.9
Quartz	1.0	1.0
Hornblende	2.0	2.0
Biotite	1.5	0.7
Clinopyroxene	0.5	0.1
Sphene	1.5	0.8
Opaques	2.0	2.6
Total	100.5	100.1

[1] Average of eight samples.

[2] Young and Brennan, 1974.

by Damon (1964, 1966) on Peach Springs Tuff in the Kingman region are 16.9±0.4 m.y. and 18.3±0.6 m.y old. The latter age agrees well with the Peach Springs dates of 18.8 and 18.2 m.y. obtained near Parker. The 16.9 m.y. date appears spurious, but this date does fit the bracket defined by the two basalt ages from the Vidal-Parker area of 17.0 and 14.5 m.y. Reasons for the age discrepancies in both areas are not clear, but even though Young and Brennan (1974) indicated that the tuff in the Kingman-Peach Springs region is a single cooling unit, my observations in a very limited reconnaissance suggest that the Peach Springs is at least a compound cooling unit, which might help to explain some of the variation in dates.

The Peach Springs remanent magnetization has been described by Young and Brennan (1974). The polarity is normal, declination 32.3°, and inclination 42.8°. No paleomagnetic study was made of this unit in the Parker area, but field polarity measurements indicate the tuff is normally magnetized.

SEDIMENTARY ROCKS

Sedimentary material makes up at least half of the Tertiary section in most areas of the Vidal-Parker region (fig. 4). These rocks are characterized by abrupt vertical and lateral changes in lithology which are difficult to represent graphically (fig. 4). The coarser clastic deposits and breccias tend to occur in the lower part of the Tertiary section. The rocks are briefly described here in three main groups: breccias; conglomerate, sandstone, siltstone, and limestone; and fanglomerate.

BRECCIAS

In the eastern and southern Whipple Mountains and Riverside Mountains, the Tertiary section is locally made up of wedge-shaped deposits of debris ranging from megabreccias that commonly resemble basement rock in place to fine-grained arkosic breccias associated with sandstone and conglomerate. In some areas the megabreccias include giant slide blocks of Paleozoic and Mesozoic(?) sedimentary rocks. The best examples are about 10 km northwest of Parker (Dickey and others, 1980), where broken but stratigraphically intact masses of quartzite and overlying limestone lie at the base of the Tertiary section. The quartzite is identified as the Esplanade(?) Formation or Queantoweap Sandstone of McNair (1951); the overlying carbonate rocks are probably the stratigraphic equivalent of the Kaibab Limestone. In the Riverside Mountains, the basal Tertiary breccias include predominantly Paleozoic and Mesozoic(?) rocks apparently derived from nearby outcrop areas of these rocks.

In most areas these breccias of Paleozoic and Mesozoic(?) rocks are overlain by coarse and fine sedimentary breccias and conglomerate almost entirely derived from granite gneiss of the upper plate. Such breccias are also commonly intercalated with andesite lavas and breccia flows, particularly in the Whipple Mountains.

The most extensive megabreccias of metamorphic rocks are in the northeastern Whipple Mountains (sec. A, fig. 4), where more than a thousand feet of gneiss megabreccia overlies andesite lavas and finer grained sedimentary rocks. The breccias were shown as Precambrian complex on the Needles sheet geologic map (Bishop, 1963) and were mapped as Precambrian basement complex by Kemnitzer (1937). These giant breccias bear an interesting resemblance to the "Amargosa chaos" of Noble (1941) and Hunt and Mabey (1966) in the Death Valley region.

CONGLOMERATE, SANDSTONE, SILTSTONE, AND LIMESTONE

Sedimentary rocks of these lithologies occur throughout the Tertiary section in most of the region. They are thin or absent in the western Whipple Mountains, and, if present in the Mopah Range, they are buried beneath the thick pile of volcanic rocks. In some areas it is possible to distinguish between sediments laid down prior to the Peach Springs Tuff and those deposited later.

Almost all the sedimentary rocks are shades of tan to brick red. The conglomerates typically consist of fairly well rounded cobbles of granite gneiss in a matrix of coarse arkosic sandstone. This material commonly grades into fine to coarse sedimentary breccias or sandstone. All the sandstones and siltstones tend to be poorly sorted and the grains are subangular. Colorful red and pink sandstones are well exposed at several places in the Colorado River Valley between Parker and Parker Dam. Brick-red sandstones are common, but in many areas bleaching results in tan or subdued reds.

Many unconformities are present throughout the Tertiary section, but one of the most persistent unconformities is found in the southern Whipple Mountains where it separates primarily lavas and breccias below from sedimentary rocks above. Sediments above the unconformity consist of locally more than 300 m of red, tan, and brown sandstone, limy siltstone and limestone, much of which is fairly thin bedded. These beds are generally less disturbed by faulting than the underlying rock and display gentle dips and open folds. These attitudes commonly steepen near the unconformity, however, which shows that much of the apparent folding is due to initial deposition on sloping surfaces. Surprisingly, little reworking of coarse fragments of older rocks occurs in these beds; some of the lacustrine limestones, which are often difficult to distinguish from limestones of pre-Tertiary age, occur abruptly within the clastic sequence, or were locally deposited directly on breccias and lava flows without incorporating any of these rocks. Temporary blockage of drainage and quiescent conditions are required to explain these phenomena. Despite careful searches, no fossils were found in the sedimentary rocks.

In some areas, such as the southern Whipple Mountains, a still younger sequence of sedimentary rocks can be mapped on the basis of an unconformity at the stratigraphic position of the Peach Springs Tuff. Here occurs an upward change to less well indurated conglomerate, and locally, the presence of cobbles of the Peach Springs. Rocks of this type are poorly exposed beneath the basaltic lavas on the north slopes of Black Peak east of Parker. In some areas they cannot be readily distinguished from the fanglomerate of Osborne Wash, which locally contains detritus, apparently reworked from these younger conglomeratic beds. Though they are not common, there is a significant increase above this unconformity in the number of clasts of gneiss derived from the lower plate of the Whipple Mountains detachment fault.

FANGLOMERATE OF OSBORNE WASH

A widespread deposit of indurated detritus occurs between the tilted and faulted Tertiary volcanic and sedimentary rocks and the overlying Bouse Formation. In the western part of the Vidal-Parker region, the fanglomerate contains little or no primary volcanic material, but eastward in the Buckskin Mountains, mafic lava flows and silicic tuffs are intercalated in it.

Rocks of this general type and age have been described from many areas along the Colorado River drainage from Lake Mead (Muddy Creek Formation, Longwell, 1963; Anderson and others, 1972) to Needles (Metzger and Loeltz, 1973), Parker (Metzger, 1965; Metzger and others, 1973), and Yuma, where it was tentatively, and probably incorrectly, correlated with part of the Kinter Formation (Olmsted and others, 1973, p. H35). Similar clastic deposits are present throughout much of the Basin and Range province, but they are well exposed only in tectonically active areas (for example, the Furnace Creek and Funeral Formations in the Death Valley area (Noble, 1941; Hunt and Mabey, 1966)).

The fanglomerate is not very thick anywhere in the region, particularly if basaltic lavas are excluded. Near Parker, it is probably nowhere more than 500 m thick.

In the Vidal-Parker area the fanglomerate consists largely of coarse brown to tan indurated colluvium, containing predominantly cobble sized clasts, but locally containing lenses of sand and boulders. In general, the unit coarsens toward the mountains. In most exposures, the deposit is sufficiently indurated to stand in near vertical walls. The clasts are predominantly Tertiary volcanic and sedimentary rocks, which help to distinguish the unit from some Pliocene-Pleistocene alluvium.

A silicic ash bed was found in the fanglomerate northwest of Parker (1.3 km northeast of the Turk mine, Parker NW. quadrangle). This ash is believed to be different from tuff beds occurring farther east in the Buckskin Mountains, and from another ash found about 4 km farther west in what was mapped as a sandy phase of the Bouse Formation (Dickey and others, 1980). A comparison of the two ashes is given in table 4. The samples are generally similar but differ in details.

At first glance these two ashes appear very similar, but both are slightly contaminated (MWC-24-75 more than MVC-59-75) with fine sand. This could explain some of the differences, but it is concluded that the two ash beds are probably different and that they are contained in two stratigraphic units, Bouse Formation and fanglomerate of Osborne Wash. Another similar ash bed occurs in the fanglomerate on the north side of the Whipple Mountains in sec. 6, T. 3 N., R. 25 E.

The fanglomerate of Osborne Wash, as mapped, probably spans a fairly long interval of time, as suggested by the dates of included basaltic rocks (table 2) in the Buckskin Mountains area. Even if some dates are in error, at least 8 million years are involved. Thus, the unit must be considered Pliocene and Miocene in age. The age of the unit is important as its base is easily recognized as a major unconformity in most areas. Only

TABLE 4.—*Comparison of ash beds in sand of the Bouse Formation and fanglomerate of Osborne Wash*

Sample No.-------------	MWC-24-75	MWC-59-75
Location---------------	SE1/4NW1/4 sec. 22 T. 2 N., R. 24 E. Parker NW quad. Sandy phase of Bouse Formation.	NW1/4NW1/4 sec. 25 T. 2 N., R. 24 E. Parker NW quad. Fanglomerate of Osborne Wash.
Refractive index of glass.	1.496	Slightly 1.500, but shards a little more devitrified than in sample MWC-24-75.
Heavy minerals		
Percent 2.88 SG[1]----	4.6	1.0
Character------------	Well rounded to angular. Biotite absent, but bleached biotite in light fraction; abundant green hornblende.	Mostly angular Biotite present; scarce green hornblende.
Light fraction		
Percent of raw sample +325 mesh----------	34	6
Percent 2.88 SG[1]----	95.4	99.0
Character------------	Shards relatively transparent.	Shards tend to be iron-stained; "striated" shards and bubble walls more prevalent.

[1] SG = specific gravity, +325 mesh fraction.

a few faults displace the fanglomerate in the Vidal-Parker region, and with but a few exceptions, they are short and have less than 3 m of offset. The beds in the fanglomerate rarely dip over 5°, but locally near steep bedrock slopes dips are as much as 35°. Most, if not all, of this dip is probably initial.

BOUSE FORMATION

The Bouse Formation, named and described by Metzger (1968), is a fine-grained, light-colored, marine- to brackish-water deposit of late Miocene and Pliocene age. It was laid down in an estuary that reached up the present valley of the Colorado River beyond Needles, Calif. In addition, deposits lithologically and faunally (Smith, 1970; Winterer, 1975) similar to the Bouse, and probably of the same origin, occur throughout the eastern Mojave Desert at elevations mostly less than about 1,000 ft (300 m), but in most areas they are buried by younger alluvium. The Bouse is an excellent stratigraphic marker, but it is only sporadically exposed in the Vidal-Parker area. A related tufa plastered on bedrock and a thin basal white marl are easily identified. Upslope, the Bouse grades into soft pink siltstone and tan sandstone. This lithology is best exposed on the south flanks of the Whipple Mountains above about 900 ft (275 m); sandy deposits believed to represent contemporaneous beach and eolian sands are found to elevations of about 1,400 ft (425 m) in that area.

The Bouse was not studied in detail, but because of its importance as a structural datum, it is discussed later in that context. However, some refinement of Metzger's Pliocene age seems warranted. He (Metzger, 1968, p. D133) reported a K-Ar age of 3.02±1.15 m.y. obtained on partially vitric ash from a bed near the base of the Bouse about 50 km southwest of Blythe. A subsequent date (Damon and others, 1978) on the same bed yielded an age of 5.47±0.20 m.y. Porous glasses are unstable chemically, however, and, where possible, are avoided in potassium-argon dating. Fritts (in Early Site Review Report, Sundesert Nuclear Plant, 1976, v. 3, sec. 2.5E, p. 4: San Diego [Calif.] Gas and Electric Co.) pointed out that statements by Smith (1970, p. 1415) show that the Bouse cannot be older than a foraminifer which underlies typical Bouse sedimentary rocks near Yuma. This fossil is regarded as marking the Pliocene-Miocene boundary (Smith, 1970, p. 1415). Considering these dates, and often cited (for example, Metzger, 1968, p. D133; Lucchitta, 1972, p. 1940) relationships between fluvial gravels and dated basalts at the mouth of the Grand Canyon (Damon and others, 1978), an age of about 5 m.y. for the Bouse seems reasonable.

CORRELATION WITH SURROUNDING AREAS

Prior to 1975, most areas of Tertiary rocks adjacent to the Vidal-Parker region had not been studied in detail. To the east, in the Artillery Mountains area, Lasky and Webber (1949) reported Eocene(?) sedimentary rocks and mafic lavas, which they called the Artillery Formation, overlain by intermediate to silicic Miocene(?) volcanic rocks, and by Pliocene(?) Chapin Wash Formation, mostly sedimentary rocks. Basalts of Quaternary(?) age capped their section. Both the silicic volcanic rocks and the base of the Chapin Wash Formation have been dated as about middle Miocene in age. (See Otton, 1977.)

Recent work by Suneson and Lucchitta (1979) to the northeast of the Vidal-Parker region in the Bill Williams–Rawhide Mountains area identified a strongly bimodal rhyolite-basaltic sequence correlative with the younger (post-Peach Springs Tuff) volcanic rocks in the Parker area. Rocks of the Bill Williams–Rawhide Mountains area gave ages of 15.1–6.8 m.y.; they are underlain by sedimentary rocks, chaotic depositional breccia, and andesitic flows, one of which gave an age of 16.5 m.y. (Suneson and Lucchitta, 1979). This age may be a little too young as the unit is overlain by the Peach Springs Tuff, which is 17–18 m.y. old (this report). An important difference in volcanism between the area studied by Suneson and Lucchitta and most of the Vidal-Parker region is the increasing abundance to the northeast of silicic volcanic rocks in the period from about 15–10 m.y. ago. The trachytes and trachyandesites of the southwestern Buckskin Mountains, described earlier, were erupted within this period and silicic ash-fall deposits within the older part of the fanglomerate of Osborne Wash increase noticeably northeastward from Parker. It is also notable that the 15–10 m.y. silicic volcanism in the Bill Williams–Rawhide Mountains area is almost precisely a time correlative of the more voluminous rhyolitic volcanism of the Nevada Test Site region 350 km to the northwest. Interestingly, both of these silicic volcanic fields lie at the northeast edge of the Walker Lane–Mojave–Sonoran Belt.

Southeast of the Vidal-Parker area in the Quartzsite quadrangle, Miller (1970) mapped a sequence of units of rhyolite, andesite, rhyodacite, and basalt, most of which are lava flows. He dated one unit, the rhyodacite, which gave an age of about 20 m.y. (Miller and McKee, 1971). Later work by consultants to San Diego Gas and Electric Co. dated four more samples of the lavas from the same general area and obtained ages of 17.4±0.7, 18.0±1.0, 19.7±0.9, and 22.4±1.4 m.y. (Early Site Review Report, Sundesert Nuclear Plant, 1976, Amendment 10, figs. 2.5-28: San Diego [Calif.] Gas and Electric Co.). The volcanic stratigraphy has not been completely worked out in the Quartzsite area, but the dates obtained suggest an age grouping similar to that of the Vidal-Parker area.

Farther south, in one of the more detailed investigations of Tertiary rocks in the eastern Mojave Desert, Crowe (1973; Crowe and others, 1979) mapped the volcanic rocks of the Picacho area and made reconnaissance studies of the rocks of the surrounding southeastern Chocolate Mountains, Calif. He obtained dates ranging from about 32 m.y. on the oldest rocks to about 26 and 23 m.y. on an overlying ash-flow tuff and an andesite lava higher in the section. A basalt, which forms widespread capping flows, was dated at about 13 m.y. He identified a tripartite stratigraphic sequence as generally consisting of a lower unit of basalt to rhyodacite lavas, a middle unit of rhyodacite to rhyolite lava and ash flows, and an upper basalt-andesite group of lavas. He suggested that the latter group (13-m.y.-old lavas) corresponds to the change to dominantly basaltic activity, which elsewhere in the Basin and Range is accompanied by the inception of basin-and-range faulting (Christiansen and Lipman, 1972). In the Picacho area, however, Crowe (1978 and written commun., 1977) believes, on the basis of detailed mapping and lithologic evidence, that basin-and-range faulting began earlier, before 26 m.y. ago. The evidence, however, is based largely on the appearance low in the section of coarse clastic deposits, which he believes could only have been derived from rising fault scarps.

In the central Mojave Desert, Armstrong and Higgins (1973) pointed out an apparent lack of volcanic rocks older than 22 m.y., a date that agrees well with the age of the oldest volcanic rocks in the Vidal-Parker region.

North of the Vidal-Parker region, in the area southwest of Lake Mead, detailed mapping by Anderson (1971, 1977), and studies by Anderson, Longwell, Armstrong, and Marvin (1972) have documented a sequence of Tertiary rocks which appear to have an age distribution and general composition similar to those in the Vidal-Parker region. There too, the change to predominant basaltic volcanism occurred around 12–14 m.y. ago.

The evidence suggests that increasingly older volcanic rocks are present from the southern Great Basin southward into the eastern and southern parts of the Mojave Desert. However, such generalizations should be made with caution until more work is done on the Tertiary stratigraphy in the large region between Lake Mead and Yuma, Ariz.

TERTIARY AND QUATERNARY DEPOSITS

COLORADO RIVER DEPOSITS

Fluvial deposits laid down after retreat of the sea from the Bouse estuary have been described in various publications (Metzger and others, 1973; Metzger and Loeltz, 1973; Lee and Bell, in San Diego Gas and Electric Co., 1976, v. 3, App. 2.5D). Lucchitta (1972) discussed the history of the river in the Basin and Range province. Magnetostratigraphic studies were made by Kukla (in Early Site Review Report, Sundesert Nuclear Plant, 1976, v. 3, App. 2.5B: San Diego [Calif.] Gas and Electric Co.) on river deposits south of Parker. He concluded, on the basis of the remanent magnetization, that the older Colorado River deposits were probably deposited in the Gilbert Paleomagnetic Epoch, which would place them in an approximate age range of 3.4–5.1 m.y. Most of the intermediate age river deposits he found to be predominantly normally magnetized, and therefore of probable Brunhes age (<730,000 years).

Fluvial gravels that predate the Bouse Formation had not been identified prior to this study. The underlying fanglomerate of Osborne Wash shows no evidence of through-going streams. Mapping in the vicinity of Parker (Dickey and others, 1980), however, identified several small areas of fluvial sediments that underlie the Bouse. The best exposure is at the west end of the bridge over the Colorado River at Parker. Other unmapped small outcrops occur under the Bouse at Headgate Rock Dam, 2 km northeast of Parker (pl. 1). The beds consist of well-sorted pebbles and sand, poorly indurated, and locally iron stained. Similar fluvial gravels, which cannot be proven to underlie the Bouse, occur in the valley that trends southeastward from near Cienega Springs (7 km northeast of Parker; pl. 1) toward Osborne Wash. At one locality about 3 km southeast of Cienega Springs, indurated well-rounded gravel is plastered on a stream-fluted outcrop of Paleozoic limestone.

The probable oldest gravels that are definitely younger than Bouse occur in a belt from Osborne Wash near Black Peak southward to east of Mesquite Mountain, and across the La Posa Plain south to Tyson Wash near the north end of the Dome Rock Mountains (pl. 1). These gravels are commonly heavily coated with desert varnish and are cemented by caliche. They occur at a maximum altitude of slightly over 900 ft (275 m) southeast of Mesquite Mountain and apparently record an early high-level course of the Colorado River some distance east of, and about 500 ft (170 m) higher than its present course. The thick deposit of river sediments exposed between Mesquite Mountain and Moon Mountain (pl. 1) is probably a deltaic deposit laid down in the early history of the river.

ALLUVIAL DEPOSITS

Alluvium of the Vidal-Parker region is fairly well exposed, because of incision of drainage related to the Colorado River. The relations of alluvial units to the older rocks and to Colorado River deposits are shown diagrammatically in figure 6, which is adapted from the geologic quadrangle map by Dickey, Carr, and Bull (1980). Details of the alluvium are not discussed here, but descriptions can be found in the geologic quadrangle maps and in a report by Southern California Edison Co. (Information Concerning Site Characteristics, Vidal Nuclear Generating Station, 1974, v. 3, App. 2.5B).

On plate 1 the alluvium is subdivided into three major units, an older, highly dissected fanglomerate-type alluvium (QTa); alluvium of intermediate (Pleistocene) age (Qa2), which has varying degrees of soil formation and characteristically displays a fairly smooth surface stained by desert varnish; and younger alluvium (Qa1) that is largely of Holocene age and is related to present drainages.

AGE OF THE ALLUVIAL UNITS

Because of the importance of the alluvium in establishing an upper limit to the age of surface faulting

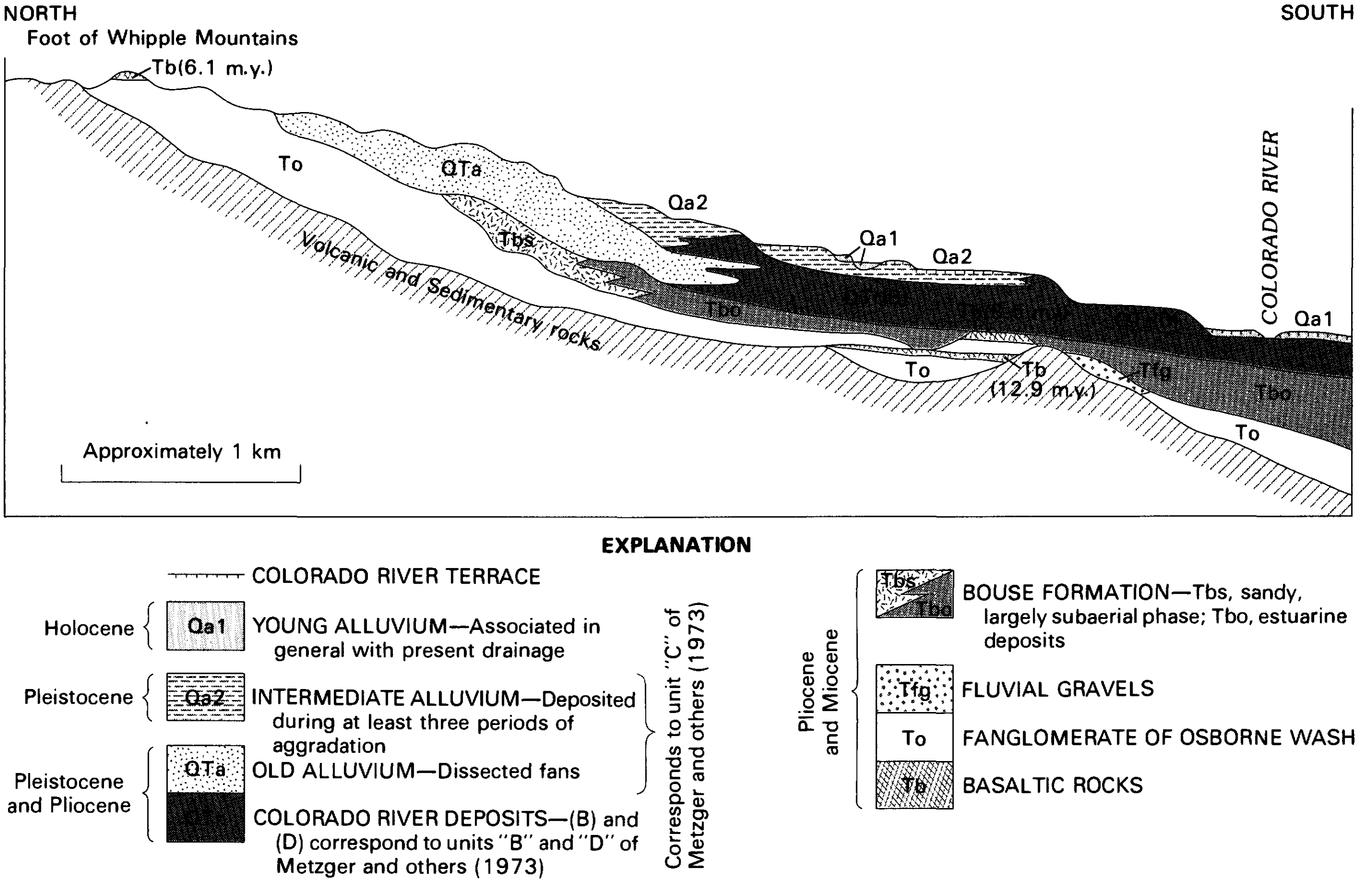

FIGURE 6.—Relation of Tertiary and Quaternary deposits between the Whipple Mountains and Colorado River in the vicinity of Parker, Ariz. Units QTa and Qa2 correspond to unit "C," units QTr(B) and QTr(D) correspond to units "B" and "D", respectively, of Metzger, Loeltz, and Irelan (1973). Ages shown are K-Ar whole-rock determinations by R. F. Marvin, U.S. Geological Survey. Ages have been corrected for new constants. Scale 1¼ in. = approximately 1 km. Large vertical exaggeration. Modified from Dickey, Carr, and Bull (1980).

in the region, a brief discussion of the age of these deposits is worthwhile. All information obtained to date indicates a complete absence of faulting in the Vidal-Parker region in alluvium of intermediate age (unit Qa2) and younger materials; a few minor faults are present in deposits as young as the old alluvium (unit QTa).

Consultants for the power companies investigated the age of the alluvium by several techniques, none of which provide a wholly satisfactory solution to the problem of absolute age of relatively young sedimentary deposits. Kukla reported (p. 19, this report) on the results of paleomagnetic studies of Colorado River deposits (QTr) which intertongue in a complex manner, principally with the old and intermediate age alluvium (fig. 6). Bull originally described (in Southern California Edison Co., 1974, v. 3, App. 2.5B) the geomorphology and characteristics of the alluvium in the Vidal region, and he estimated ages of the units based on their similarity in weathering and soil development to Pliocene-Pleistocene alluvium along the Rio Grande Valley in New Mexico, pointing out that differences, chiefly in rainfall, in the two areas tend to make his estimates of age conservative; that is, the estimates in the Vidal area are probably minimum ages. Ku (in Information Concerning Site Characteristics, Vidal Nuclear Generating Station, 1975, v. 5, App. 2.5G, Southern California Edison Co.), reported several ages obtained by the U-Th disequilibrium dating method on carbonate in soils developed on the intermediate alluvial unit (Qa2), and he reported a date on a mammoth tusk recovered from Colorado River deposits. No consistent dates were obtained in the first samples; several of the ages fell well outside the estimates made by Bull. A second attempt was made to date a specific fan in the intermediate alluvium (unit Qa2) by digging down uniform distances from the varnished pebble surface and carefully scraping caliche off pebbles. This method, done on samples from two separate fans, gave fairly consistent values that clustered around 80,000 years (T. Freeman, Woodward-McNeill and Assoc., oral commun., 1977).

With one exception, work for this report did not attempt dating of carbonates. One sample of spring travertine collected in the NW¼ sec. 3, T. 2 N., R. 22 E., east of the Mopah Range (Carr and others, 1980) gave a U-Th age of 20,000±6,000 years (J. N. Rosholt, U.S. Geological Survey, written commun., 1976). The large possible error reported was due to the presence of approximately 37 percent silicate minerals. The soft travertine that was sampled is directly overlain by a thin mantle of alluvium belonging to unit Qa2. The usual varnished surface material of this alluvium contained numerous worked flakes and several arrowheads which also had varnish coatings. No spring is at this location now, but the presence of the old artifacts indicates that water was available at the spring that deposited the travertine at times during the Pleistocene. Relations at the site suggest, but do not prove, that the alluvium is younger than all the travertine, but the date of 20,000±6,000 years is in general agreement with ages of two rat middens (Wells and Berger, 1967) in the nearby Turtle Mountains dated at about 13,900 and 19,500 years. Both middens contain abundant evidence that pine woodlands existed in the area at that time. Such vegetation would have required considerably more moisture than at present, as would the presence of springs.

STRUCTURE AND TECTONICS OF THE VIDAL-PARKER AREA AND SURROUNDING REGION

GENERAL SETTING

The region discussed here lies in the Basin and Range physiographic-structural province about halfway between the San Andreas fault zone and the southwestern margin of the Colorado Plateau province (pl. 2; fig. 2). Little structural detail is known, and the great width of the alluviated valleys and complexity of the geology assure no early change in this situation. Plate 2 shows the general tectonic setting of the Vidal-Parker region in relation to the eastern Mojave Desert. The predominant structural grain of the region is northwest trending, but to the west are the Transverse Ranges characterized by a series of active east-trending faults and underlain by areally abundant granitic and metamorphic rocks. Tertiary rocks are absent or thin throughout that area. The Transverse Ranges abruptly terminate eastward at the Sheep Hole and Coxcomb Mountains, which mark the west edge of a well-defined zone of northwestward-trending ranges and valleys which extends several hundred kilometers from the central Mojave Desert southeastward into southwestern Arizona. This structural-topographic trend spreads westward into the western Mojave Desert north of the Transverse Ranges, but there it is marked by a number of northwest-trending active faults. About 150 km to the southwest of the Vidal-Parker region lies the San Andreas fault system and the Salton Sea tectonic depression. Northeast of the Vidal-Parker region is a persistent northwest-trending lineament—a discontinuity marked by convergent topographic trends and southward termination of northerly trending ranges and valleys: in Arizona—the Big Sandy Valley, Hualapai Valley, Hualapai-Cerbat Mountains, Sacramento Valley, Black Mountains, Colorado River Valley; and in Nevada and California—the Dead-Newberry Mountains, Piute-Eldorado Valleys, and the McCulloch Range. This lineament is one of the most prominent structural-topographic trends in the southwestern United States, as pointed out long ago by Hill (1902, 1928) and Ransome (1915), and more recently by Kelley (1955), Albritton and Smith (1957), and Barosh (1969).

Distribution of rocks (pl. 2) is an important aspect of the structure of the eastern Mojave Desert. Unmetamorphosed or slightly metamorphosed granites decrease in volume eastward from the Transverse Range area; along the Colorado River Valley they are much less abundant, but farther northeast they are a prominent part of the exposed rocks along the foot of the Colorado Plateau. Recognizable Paleozoic rocks in the eastern Mojave Desert are apparently limited to the Mojave-Sonoran Belt, although metamorphosed parts of the Paleozoic section may be present in adjacent areas. Clastic rocks of Mesozoic and Tertiary age (unit CzMzl, pl. 2) of the Livingston Hills Formation type appear to be present chiefly in a zone paralleling and southwest of the edge of the Mojave-Sonoran Belt. Sedimentary rocks of Mesozoic age, and possibly younger, are probably present in the belt, but they are apparently much thinner within the belt and lack the thick conglomerates of the Livingston Hills type sequence. This abrupt southwestward thickening and coarsening of the Mesozoic rocks also occurs across the Texas lineament in southwestern Texas (Albritton and Smith, 1957).

At first glance Tertiary rocks seem to be rather widely and uniformly distributed throughout the eastern Mojave region (pl. 2). However, closer inspection reveals that thicker volcanic rocks occur near major centers, particularly for silicic extrusive rocks, located in the Kofa, Castle Dome, and Chocolate Mountains of Arizona, in the southern Black Mountains, Ariz., and in the mountains 15–40 km northwest of Goffs, Calif. In all these areas there are thick sequences of rhyodacite and rhyolite lava flows, together with ash-flow and airfall tuffs. In addition, a major basaltic eruptive center occurs in the Mohon Mountains area at the edge of the Colorado Plateau. Very little has been published about these centers so that details of their eruptive history are largely unknown. Smaller centers, largely rhyodacitic, are scattered about the region from the Eldorado Mountains of Nevada (Anderson, 1977) to the Mopah Range, Calif. (Carr and others, 1980) and to the Picacho area of California (Crowe and others, 1979) 35 km north of Yuma, Ariz. In most other areas in the eastern Mojave Desert, volcanic rocks are of lesser volume and are highly diluted with sedimentary materials. These sedimentary rocks are commonly composed of coarse detritus of Miocene and Pliocene age.

GEOPHYSICS

As more information becomes available, the role of geophysics is increasingly important in understanding the tectonic history of the eastern Mojave Desert. The metamorphism, complexity of the geology, and the presence of broad areas covered by alluvium, make the need for geophysical studies in this region especially critical. Fortunately, work in recent years has contributed much new geophysical information. In this report, work in the fields of seismology, gravity, and aeromagnetics will be briefly discussed and attempts will be made to relate some of this data to geology and structure.

SEISMOLOGY

At the inception of the geologic studies in the Vidal-Parker region, it was recognized that documentation was needed to confirm the suspected aseismic character of the eastern Mojave Desert. As a result, the U.S. Geological Survey, on behalf of the Nuclear Regulatory Commission, from 1974 to 1977 operated a seismic net in the Mojave Desert as far east as Parker, Ariz. Station locations are shown in figure 7. A similar, dense network of stations has operated in the much more seismically active area to the west of long 116° W.

According to Gary Fuis (written commun., 1976, 1977) of the U.S. Geological Survey, then at the Seismological Laboratory at the California Institute of Technology, more than 2 years of monitoring recorded only a very few small earthquakes in the area east of the aseismic area boundary shown on plate 2. Two small events of about magnitude 1 were recorded near lat 34° N., long 115° W. in May 1976, and one of magnitude 1.2 at approximately lat 34°45′ N., long 115°05′ W. in October 1974. A few other events recorded are probably explosions judging from location and signal character. The current extremely low level of seismicity in the eastern Mojave Desert confirms earlier records made from more distant stations back to the 1930's (Hileman and others, 1973) that show the area to be essentially aseismic. During the same recording period and earlier, the western Mojave Desert, in contrast, has been seismically very active.

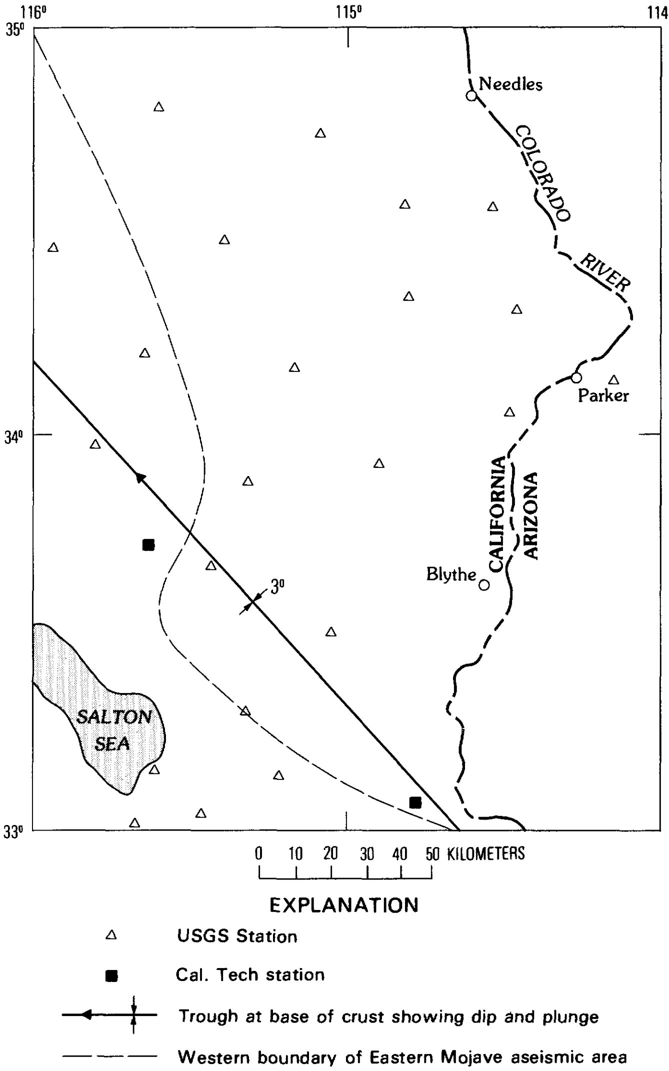

FIGURE 7.—Seismic stations in the eastern Mojave Desert, 1974–77.

The Mojave Desert has been considered to be a somewhat anomalous part of the Basin and Range province with an upper mantle velocity generally in excess of 8 km/s (Prodehl, 1970; Stuart and others, 1964) and a crustal thickness less than about 30 km.

Using explosions, Gary Fuis (written commun., 1976) has examined travel times and depths to the base of the crust in southeastern California. He tentatively concluded that the crustal thickness varies from about 33 km near Barstow to around 20 km in the Imperial Valley. In the area along the Colorado River, crustal thickness was estimated to be about 26 km. The shape of the Mohorovicic discontinuity (base of crust) obtained by contouring depths suggests an asymmetric trough plunging northwest along an axis lying about halfway between Blythe and the Salton Sea (fig. 7). Refraction profiles suggest a dip of about 3° SW. on the northeast flank of the trough. The southwest side of the trough appears to be steeper. On a refraction profile from Corona, Calif., to Parker, Ariz., Gary Fuis (written commun., 1976) noted a bend in the P_n branch of the traveltime curve in the vicinity of the Little Maria Mountains seismic station, with a slightly lower velocity, about 8.0 km/s, farther east in the vicinity of Parker, Ariz. Thus, the Vidal-Parker region probably lies just northeast of a northwest-trending change in the upper mantle velocity and is underlain by a crustal thickness of about 26–27 km. To the west the "aseismic boundary" crosses the crustal thickness trend lines at a fairly small angle.

MAGNETICS

High-level aeromagnetic maps of the eastern Mojave Desert are available for Arizona at a scale of 1:1,000,000 (Sauck and Sumner, 1971) and for California east of long 116° W. and north of lat 33°30′ N. at a scale of 1:250,000 (U.S. Geological Survey, 1975). In addition, a ground magnetic map of the area between Blythe and Desert Center, Calif., was made by Rotstein (1974). For this report, aeromagnetic measurements of the region are compiled on plate 3. A low-level aeromagnetic map issued by the U.S. Geological Survey (1981) of the Needles 2° sheet was not available at the time of the compilation, but the new map provides some useful supplementary data for the Vidal-Parker region.

Most of the Vidal-Parker region is characterized magnetically by diffuse anomalies of variable orientation and relatively low amplitude. Exceptions include areas of granitic rocks that produce two strong positive anomalies, one between the Sacramento and Chemehuevi Mountains, the other over the western Turtle Mountains. Weaker positive anomalies are present over the northwestern Whipple and western and eastern Buckskin Mountains. Striking anomaly trends are present both northeast and southwest of the Vidal-Parker region; both are closely related to strongly magnetic granitic plutonic rocks (pls. 2 and 3). In general, the 100-km-wide belt between these two areas of strong anomalies is magnetically weak, possessing no more than a 200-gamma relief on either side of the 0-gamma contour. At the flight heights of about 8,000–11,000 ft, important structural details and volcanic rocks in most of the region on plate 3 do not produce significant anomalies; several exceptions are worth noting: (1) At the north edge of the map area (at about long 115°15′ W.), a strong negative anomaly is present that coincides nicely with a gravity negative anomaly suggested by Healey (1973) as due to a caldera structure. Presumably, the caldera is filled with a thick section of reversely magnetized lavas and ash-flow tuff. (2) In the northeast corner of the map area, strong positive anomalies are associated with the Mohon Mountains volcanic center. (3) To the south, in Arizona, volcanic rocks are at least partly responsible for moderate anomalies in the Kofa, Little Horn, and southern Plomosa Mountains area.

Despite the local diversity of trends, the regional weak-anomaly magnetic belt has a distinct northwest trend, as do many of the anomalies within it, reflecting the important northwest-trending structural grain of the region. Significantly, this trend is lacking northeast of a line trending N. 55° W. from about lat 34°00′ N., long 113°00′ W. to lat 35°00′ N., long 114°45′ W. This same geophysical trend continues both northwest beyond the edge of the map area, closely following the California-Nevada border, and southeast through Arizona toward and beyond Phoenix. This change in magnetic character coincides well with the northeast edge of the Mojave-Sonoran Belt.

The aeromagnetic map also shows other large features of structural significance. In Arizona, the northeast-trending Buckskin, Harcuvar, Harquahala, and Big Horn Mountains all have similar positive magnetic anomalies, but the trend of the group of anomalies is distinctly northwest; the lower gamma levels between ranges probably are due partly to greater distance of the bedrock from the flight level.

Likewise, in California, in the area at the east end of the Transverse Ranges (Pinto-Eagle Mountains) there is very little indication of the prominent east-west structure, but instead, a strong N. 60° W. magnetic trend. This same distinct trend, but with weaker anomalies, persists as far northeast as Cadiz Valley, and as far east as the Granite, Little Maria, and Big Maria Mountains. This northeast limit to the pattern of prominent northwest magnetic trends, largely unaffected by the trends of the Transverse Ranges, marks the southwest edge of the Mojave-Sonoran Belt (pls. 2 and 3). The lack of expression in the magnetics of the east-west trend of the eastern Transverse Ranges is compatible with the crosscutting nature and general youthfulness of these structures.

Another feature of note is the relatively flat, distinctly negative magnetic gradient associated with the Mesozoic-Tertiary sedimentary rocks of the Livingston Hills Formation type. This gradient is evident in a zone extending southeastward from the south end of the Coxcomb Mountains through the Palen, McCoy, and Dome

Rock Mountains to the southern Plomosa Mountains (pl. 3). Other areas of rocks (pl. 2) probably correlative with the Livingston Hills Formation in southwestern Arizona are likewise marked by low-amplitude negative anomalies, as, for example, parts of the Castle Dome and Middle Mountains. This magnetic signature reflects the thick, relatively nonmagnetic character of these sedimentary rocks and the probable absence of extensive granitic rocks beneath them. However, the same magnetic trend continues northwestward beyond outcrop areas of the Livingston Hills type rocks, which suggests that deeper, more fundamental factors are responsible, such as the subcrustal northwest-trending boundary mentioned in the section on seismology.

The U.S. Geological Survey (1981) aeromagnetic map of the Needles 2° sheet was flown at 1,000 ft above terrain and provides a much more detailed view of the magnetic characteristics of the rocks in the Vidal-Parker region. Volcanic rocks in two main areas, the Mopah Range and western Buckskin Mountains, exhibit typical high-amplitude small anomalies. In the Mopah Range the anomalies are nearly all elongated in a northwesterly direction, but in the Buckskin Mountains trends are much less consistent. These trends reflect the strong northwest structural grain caused by faulting in the Mopah Range area, and general lack of such faulting in the Buckskin Mountains. Both northwest and northeast trends are visible on the low-level Needles sheet; however, many areas, such as the Chemehuevi and Whipple Mountains, fail to show prominent trends associated with Tertiary rocks in the upper plate of the Whipple Mountains detachment fault. This is perhaps another indication of the "thin-skin" and highly dismembered nature of the upper plate rocks, which tend to be weakly magnetic in much of the area, despite their high content of granitic material. One particularly obvious regional magnetic lineament is shown by the low-level map: a persistent gradient and discontinuity trends about N. 60° E. and extends about 75 km from the Turtle Mountains on the southwest to the Mohave Mountains on the northeast (pl. 2). The linearity and great length of this discontinuity in the magnetic contours indicate a prominent fault zone probably occupies this position. It lies just outside the geologically mapped area on plate 1, and much of it is buried beneath alluvium in Chemehuevi Valley. The trend and position of this feature is very close to that shown farther southeast by the northeast-trending parts of the Buckskin, Harcuvar, and Harquahala Mountains (pl. 2). Similar northeast structure trends are present in the Old Woman Mountains to the northwest of the Vidal-Parker area. The significance of these observations will be discussed later in this report.

GRAVITY

A gravity map of the eastern Mojave Desert region has been compiled for this report (pl. 2). Like the aeromagnetic map (pl. 3), the Vidal-Parker region shown on plate 2 also shows small gravity anomalies that generally have nonlinear low gradients, except for a relatively steep linear gradient that parallels the belt margin on the northeast. Gravity does not appear to define the southwest margin of the belt as well as seismic information or aeromagnetic data, although farther southwest, the Salton trough and San Andreas fault zone are marked by a prominent northwest-trending gravity high. With the principal exception of the Salton trough, the gravity anomalies fit the present topography and bedrock quite well—the gravity highs are over the mountains, the lows over the basins. In this regard, a good correlation appears to exist between the gravity highs and areas of metamorphic rocks in general, particularly the lower plate of the Whipple Mountains detachment fault. Notably, there are only a few steep linear gradients like those that characterize deep structurally active valleys elsewhere in the Basin and Range province.

Several linear gravity gradients suggestive of faulting or correlative with known faults should be pointed out. In the vicinity of Needles, a strong linear gravity gradient trends northwest and is paralleled at the surface by fault scarps in Quaternary alluvium. These faults were called the Needles graben (Information Concerning Site Characteristics, Vidal Nuclear Generating Station, 1975, v. 2, p. 2.5-141 and Amendment 6, p. 2.5-141, Southern California Edison Co.). Along Bouse Wash on the northeast side of Mesquite Mountain is a 20-km-long northwest-trending steep gravity gradient suggestive of faulting; a small fault in the Bouse Formation has been observed here (pls. 1, 4), but no younger beds are known to be faulted. A similar linear gravity gradient, but trending northeast, is present on the northwest side of the Mule Mountains about 25 km southwest of Blythe, Calif. There, also, no faulting is observed in Quaternary deposits, but the steepness of the gradient indicates a density contrast that is probably due to a steep contact between the metamorphic bedrock and buried Bouse Formation or Colorado River deposits. This contact could represent a fault scarp against which the lower density Bouse or the river deposits were accumulated; they may or may not be involved in the faulting.

About 20 km north of Blythe is another feature, the Blythe graben (Information Concerning Site Characteristics, Vidal Nuclear Generating Station, 1975, v. 2, p. 2.5-141, Southern California Edison Co.) that is similar in some ways to the Needles graben. Several scarps in alluvium, probably alluvium of intermediate age (Qa2), are present along the northeast side of the northwest-trending gravity-defined trough that lies between the McCoy and Big Maria Mountains. This trough is about 40 km long and is one of the best defined valleys filled with low-density material in the region. The feature is important to the interpretation of the structural geology, not only because it has associated Quaternary faulting, but also because it lies near the southwestern margin of the tectonic belt defined by other geophysical and geologic data.

A major gravity feature of importance is the regional high that extends up the Colorado River Valley from the Imperial Valley northward to the Lake Mohave area, 50 km southeast of Las Vegas, Nev. On first examination it would appear that this high could be entirely a result of topography (pls. 2, 5), and, indeed, a fairly consistent general relation exists between elevation and gravity—the 1,000-ft elevation contour roughly approximates the 50 mgal gravity contour, and the 2,000-ft contour, the 75 mgal contour. However, the regional geologic map shows that the distribution of relatively unmetamorphosed granitic rocks follows the same general pattern; that is, granites are volumetrically more abundant in the western and northwestern parts of the map area than they are along the Colorado River Valley at elevations below 2,000 ft or so. This relationship suggests that isostatic compensation may have influenced the course of the Colorado River, localizing it in an area of slight sagging due to slightly heavier crust, and that the general match between gravity and topography is only partly the result of stripping of bedrock from the valley.

The gravity map (pl. 2) suggests other significant relationships in the Vidal-Parker region. A closed gravity high, highest in the Vidal-Parker region, coincides with the Riverside Mountains and extends across the Colorado River Valley to include the Mesquite Mountain area, which suggests that the rocks making up the lower plate of the Whipple Mountains detachment fault in the Riverside Mountains extend across to Mesquite Mountain. However, as exposures of metamorphic rock on Mesquite Mountain include no Paleozoic carbonate rocks like the Riverside Mountains, it seems likely that the carbonate rocks are present at depth beneath Mesquite Mountain. Although a more or less continuous gravity high encompasses the Big Maria and Riverside Mountains and Mesquite Mountain, each area has a separate, closed anomaly, and a suggestion of a right-lateral offset of the Mesquite Mountain–Riverside Mountains gravity highs occurs along a northwest-trending fault zone that may extend from the Mopah Range southeastward to the Plomosa Mountains (pl. 4).

One of the more prominent gravity lows in the Vidal-Parker region lies along the northeast flank of the Mopah Range. A small closed low, partly over alluvium, is present in this area in a location which suggests that it may mark the main eruptive center for the rhyodacitic lavas, tuffs, and breccias of the Mopah Range. Several plug domes similar to adjacent lavas are exposed a short distance southwest of this low.

LEVEL LINE

By D. D. DICKEY

In 1930-32, the Metropolitan Water District of Southern California completed a line of first-order leveling extending along the route of the Colorado River aqueduct from the Colorado River near Parker, Ariz., to Los Angeles, Calif. In the fall of 1975, about 20 miles of this line was releveled by the Metropolitan Water District under a contract with the U.S. Geological Survey. The releveled segment was between the west portal of the Whipple Mountain tunnel westward to a point about 1.5 miles west of Vidal Junction, Calif. (fig. 8). Eighteen of the original 19 stations in this interval were recovered. All stations in the 1975 survey were found to be slightly positive with respect to an arbitrarily chosen zero point at the east end of the level line. The unadjusted measurements, bench to bench, were compared for the two surveys (fig. 8). First-order closure for the line permits a difference of 24 mm in elevation over the length of the survey. One station had a change exceeding this amount, +54 mm at bench mark 966, (Sta. 20X), 1½ miles northeast of Vidal Junction. The three bench marks to the west of bench mark 966 had measured differences of +21 mm and the next two east of it had measured differences of +23 and +24 mm. All these bench marks were inspected on the ground and were apparently undisturbed.

The reason for the anomalous elevation change of bench mark 966 is not known. As the anomalous station was elevated, subsidence apparently may be eliminated as an explanation. Possible explanations include surveying error in the original survey, uplift due to geologic structure, and uplift due to expanding clays in the Bouse Formation beneath the bench mark, which is located about 200 ft from the aqueduct and slightly downslope from it. The area immediately surrounding the bench mark was examined for youthful geologic structures, but none were found. It should be noted, however, that bench mark 966 is located in a general zone of buried northwest-trending faults (pls. 2, 4) and is above the upthrown side of one of them. Thus, preliminary evaluation of the releveling data indicates

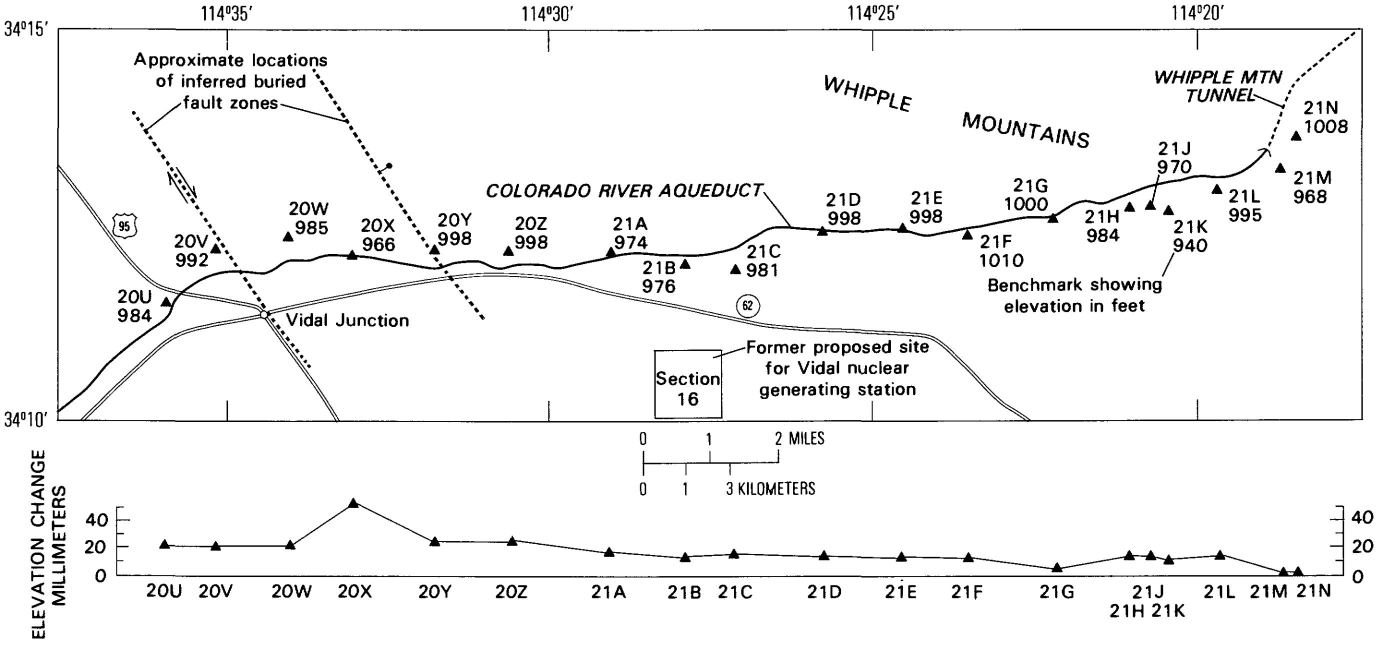

FIGURE 8.—Map and profile along part of the Colorado River aqueduct showing elevation differences between surveys in 1931 and 1975. Station 21N held constant. Station 21D not recovered in 1975. Surveyed by Metropolitan Water District of Southern California. Arrows on inferred fault zone show direction of movement; bar and ball on downthrown side.

changes that are within the allowable survey error, with the exception of bench mark 966, whose anomalous position is probably not related to structural movements, but this cannot be proven with existing data.

The series of first-order bench marks along the aqueduct, together with a trilateration net also surveyed by the Metropolitan Water District in the 1930's, offers an opportunity to pursue geodetic measurements, should reactor siting interest in the area be revived.

STRUCTURES IN PRE-TERTIARY ROCKS

Although structures in rocks older than Tertiary were not mapped in detail in most parts of the Vidal-Parker region, some important information was gained and is summarized here.

As few places exist in the area where the older Tertiary rocks are in original depositional contact with undisturbed basement rocks, determination of the age of certain faults and other features is difficult. In addition, the difficulty is compounded by juxtaposition of basement rocks in two plates by middle Tertiary detachment faulting. Considering the episode of extension and dismemberment that accompanied this event, it would seem reasonable to assume that pre-Tertiary rocks, largely metamorphosed, would everywhere be structurally complex. However, in some parts of the Vidal-Parker region at least, this does not appear to be the case. In the eastern Whipple Mountains, for example, are large areas of nearly total exposure of mylonitic lower plate metamorphic rocks (pl. 1). Reconnaissance indicates that in much of this area these lower plate rocks were not highly faulted and were not tightly folded after mylonitization. Dips of the foliation rarely exceed 25° and in most places are monotonously consistent. Terry (1972, p. 62) described the Whipple Mountains as an eroded dome elongated in a northeast direction. Direction of dip is generally radial to the center of the higher eastern part of the mountains. The western one-third of the lower plate rocks in the Whipple Mountains is somewhat more structurally complex, however. A series of northwest-striking, probably high-angle faults separates the western area from the less disturbed rocks to the east. In addition, locally numerous dikes and sills of dioritic rocks invade the metamorphic country rock; attitudes of these intrusive bodies are highly variable. Westward toward the Mopah Range, structural disturbance of the metamorphic rocks appears to increase, and granitic rocks of probable pre-Tertiary age are separated by low-angle faults from dike-riddled metamorphic rocks. Reasons for the westward-increasing structural complexity in pre-Tertiary rocks of the Whipple Mountains are unknown. It seems likely, however, that two major regional fault zones may be partly responsible: one located through the narrow west-central part of the Whipple Mountains (Chambers Well fault zone), the other between the Whipple Mountains and Mopah Range (Vidal Valley fault zone; pls. 1, 4). The northwest-trending part of Chemehuevi Valley and the postulated Tertiary volcanic center, suggested by gravity and aeromagnetic anomalies, may be located along these fault systems. A prominent northwest-trending fault in the Mopah Range mapped by Carr, Dickey, and Quinlivan (1980) shows good evidence of right-lateral strike-slip displacement. To the southeast, a parallel major fault has been mapped through the Tertiary rocks, and it may connect across the Colorado River Valley with the fault that is suggested by a gravity gradient at the northeast side of Mesquite Mountain. Thus, faulting in the metamorphic rocks in the western Whipple Mountains appears responsible for localizing some major Tertiary structure.

The Mesquite Mountain area (pl. 2) south of Parker appears to be a fairly simple north-striking westward-dipping monocline in the metamorphic rocks, but if, as suggested under the section on gravity, it represents a section similar to part of that in the Riverside Mountains, structural complexity must intervene in the area separating the two sections.

Another important fault zone of probable pre-Tertiary age appears to be located along the Lake Havasu-Colorado River course. It also trends northwest, and at least one branch extends southeastward up the Bill Williams River Valley. A little farther to the northeast, still another important subparallel fault crosses the Bill Williams River at a small angle and trends southeastward about 40 km to the vicinity of Midway, Ariz. (pl. 2).

The Riverside Mountains are the most structurally complex of the ranges in the Vidal-Parker area (Carr and Dickey, 1980). The northern Riverside Mountains appear to be essentially a faulted monocline or anticlinal limb dipping northwest and striking northeast. In the southeastern part of the range the strike swings gradually to a northwest direction (Hamilton, 1964). Upper Paleozoic rocks in the eastern part are separated from underlying, probable Precambrian rocks by a persistent thrust fault that dips gently westward in most places. Complicated faulting within the Paleozoic rocks is not well understood, but the principal style is that of reverse faults dipping westward at slightly steeper angles (40°-50°) than the bedding, resulting in several repetitions of the section. Interspersed with the reverse faults are several low-angle normal faults dipping about as steeply as the bedding. One of the main reverse faults flattens eastward to become a thrust fault. Probably many low-angle faults are present in addition to those mapped. Although reverse and drag folding occurs on some of the faults, only minor appressed folding and no overturned folding was observed, at least in the northern Riverside Mountains.

Origin of the structure in the lower plate rocks of the Riverside Mountains is unknown. The northeast structural trend is counter to the persistent northwesterly regional direction so widely developed in rocks of the upper plate of the Whipple Mountains detachment fault. It is possible the observed features are partly related to forceful emplacement of the granitic intrusive in the West Riverside Mountains. An alternative explanation is that the structure in the Riverside Mountains is a result of compression and drag folding along major strike-slip faults passing between the Riverside and Big Maria Mountains. If so, the direction of drag would seem to fit left- rather than right-lateral faulting. Right-lateral strike-slip faulting was suggested by Hamilton and Myers (1966, p. 530–531) to be an extension of the Death Valley fault zone into the eastern Mojave Desert. Faulting with northwest trend and a component of right-lateral strike-slip displacement is probably present between the Riverside Mountains and Mesquite Mountain (See "Gravity," p. 25). This zone of faulting may be similar to that described by Miller and McKee (1971, p. 720–721) in the southern Plomosa Mountains, where Miller (1970) mapped thrust faults cut by younger strike-slip faulting that offsets Tertiary volcanic rocks. An area of deformed Paleozoic rocks in the Plomosa Mountains is described by Miller and McKee (1971, p. 718) as being unquestionably correlative with deformed Paleozoic rocks mapped by W. B. Hamilton in the Big Maria Mountains. I agree that the rocks are similar, but suggest that, on the basis of a very similar style of faulting and lithology, the deformed Plomosa Mountains section of Miller is more like the upper Paleozoic section in the Riverside Mountains. Both sections lie beneath major thrust systems, but they are different in that Miller has good evidence that at least some of the thrusting in his area is older than a 20-m.y.-old rhyodacite lava; whereas, in the Riverside Mountains and elsewhere in the Vidal-Parker region, some thrust or detachment-type faulting continued well into the Miocene (to at least as late as about 14 m.y. ago). In both deformed sections in the Riverside and Plomosa Mountains, bedding and fault planes are subparallel, and one is never quite sure whether individual parts of the section have been thickened or attenuated. As stated previously, in most places in the Riverside Mountains the reverse faults dip a little steeper than the beds, resulting in repetition of the section. This also seems to be the case in the deformed Plomosa Mountains section, but in both areas faults that omit parts of the section are also present, and it is not always possible to determine whether these are normal (hanging wall down) faults or reverse faults dipping at angles less steep than the bedding. In the Riverside Mountains, however, I believe that most of the faults are reverse (hanging wall up) and that the repetition or attenuation is due to varying relationships between the dip of the fault planes and bedding. No isoclinal folding appears to be developed in the northern and central Riverside Mountains, but Hamilton (1964) mapped fairly numerous folds of this type in the southern Riverside Mountains and Big Maria Mountains.

Hamilton (1971) described the Paleozoic rocks in southeastern California as occurring mostly as "isoclinal synclinal keels in polymetamorphic plutonic basement rocks." Such a configuration requires overturning of parts of the section; I found no evidence for large-scale overturning in the northern Riverside Mountains. I believe the basic style of pre-Tertiary structure, within the Mojave-Sonoran belt, at least, is that of repetition of sections by semiconcordant (with bedding) reverse faulting, with only local appressed folding, plastic deformation, or attenuation on near bedding-plane faults. It is believed that strike-slip faulting at this stage may have begun as a series of tear faults in major thrust sheets whose roots are represented by reverse faults, such as those found in the Riverside Mountains.

Whereas the northwest-trending extensional structural grain developed in mid-Tertiary time is the most obvious structural feature of the terrain in the Vidal-Parker region, it should be remembered that the older rocks display evidence of large-scale structures oriented northeast-southwest. Basically, this trend in the pre-Tertiary rocks appears to be a series of large northeast-trending synclines and anticlines or "welts" displayed largely in the cores or lower plate rocks of the Whipple Mountains detachment fault (fig. 9). These features are evident in the geophysics (pls. 2, 3), topography (pl. 5), and local structural trends as seen in the Riverside and western Buckskin Mountains (pl. 4). As pointed out earlier, geophysical trends show evidence of northeast trends. One such geophysical lineament (pl. 2), shown best by the low-level aeromagnetic map (U.S. Geological Survey, 1981), is probably a fault zone, but the extent of its involvement with Tertiary rocks has not been determined.

TERTIARY STRUCTURES

Several authors have referred the cores of the Whipple Mountains and some adjacent ranges to a tectonic style termed "metamorphic core complex" (Davis and Coney, 1979; Shackelford, 1980). The exact timing, cause, and interrelationship of events in this process remain to be determined. In the Vidal-Parker region, stratigraphic, isotopic, and structural information point rather clearly to a Tertiary, probably middle-Tertiary, age for the principal development of the gneissic mylonitic range cores.

A number of aspects of Tertiary tectonics in the Vidal-Parker region are striking: (1) semicircular or northeasterly elongated uplifts exposing range cores with well-developed mylonitic carapaces; (2) a low-angle regional detachment surface separating the underlying range cores from highly extended, less metamorphosed crystalline rocks of Paleozoic and Mesozoic age, and unmetamorphosed volcanic and sedimentary rocks of Miocene age; (3) a regionally persistent, almost pervasive, northwest-trending structural grain in the rocks above the detachment surface; (4) abrupt truncation of the highly deformed rocks by essentially undeformed fanglomerates and volcanic rocks of late Miocene and Pliocene age; and (5) an obvious lack of deep structural basins typical of the Great Basin and other parts of the Basin and Range province.

Working out details of the structure in Tertiary rocks of the eastern Mojave Desert region is difficult because of the abruptly changing stratigraphy and the scarcity of recognizable marker beds. Fortunately, a distinctive unit, the Peach Springs Tuff, is found at scattered locations and provides a partial key to correlation of major unconformities and episodes of faulting from one range to the next.

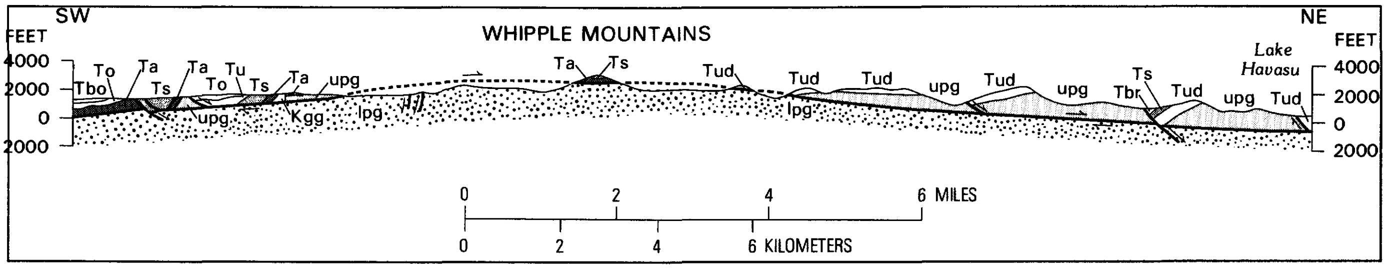

FIGURE 9.—Section through the eastern Whipple Mountains showing configuration of the Whipple Mountains detachment fault. Location of section shown on plate 1. Alluvium omitted. Tbo, Bouse Formation (late Miocene and Pliocene); To, fanglomerate of Osborne Wash (Miocene); Tu, Tertiary rocks, upper part (Miocene); Ts, sedimentary rocks (Miocene); Ta, andesite and granitic breccias (Miocene); Tud, Tertiary rocks, undivided (Miocene); Tbr, breccia (Miocene); Kgg, gneissic granite (Cretaceous); upg, upper plate granite gneiss (Mesozoic, Paleozoic, and older(?)); lpg, lower plate gneiss (Mesozoic(?) and older). Heavy lines, faults; arrows show direction of movement.

STRATIGRAPHIC-STRUCTURAL RECORD

The Tertiary stratigraphic section, though variable in detail, records some general episodes that provide clues to the structural development of the area. In the eastern Whipple Mountains and Riverside Mountains, the lower part of the section, as described earlier, contains much very coarse breccia and poorly sorted conglomerate interspersed with andesitic lava flows (secs. A, C, E, fig. 4). These breccias consist in large part of clasts whose derivation is recognizable. They have not been precisely dated, but some must be as young as 20 m.y., as they intertongue locally with andesites of that age. Clearly, these breccia deposits came from nearby topographically steep slopes if they traveled by conventional sliding downslope. However, other evidence of nearby steep slopes is not abundant; the breccias lie depositionally on a surface developed across the gneiss, which, prior to extensional faulting, apparently had little relief. In the Whipple Mountains, the breccias apparently contain no rocks derived from the now-exposed core or lower plate, but, in the Riverside Mountains, rocks from both the upper and lower plates are found, indicating that in the latter area denudation of the lower plate rocks had begun. Similar breccias are reported by Shackelford (1980) and Lucchitta and Suneson (1977b) in the Rawhide Mountains area. In the Buckskin and western Whipple Mountains and outside the Vidal-Parker region in the Chemehuevi and Sacramento Mountains, reconnaissance indicates breccias are locally present but less common. Despite the now pervasive northwest structural grain in the region, there is a strong suggestion that considerably less lithologic change takes place in the Tertiary rocks in a northeast to southwest direction than in a northwest to southeast direction. Stated another way, lithologic similarities appear much stronger athwart the present structural grain in a direction parallel to that of later extension. For example, Tertiary rocks in the Riverside Mountains are generally similar to those in the Buckskin and eastern Whipple Mountains, but volcanic rocks of the Mopah Range are most like those found in the outlying hills in eastern Chemehuevi Valley. Supporting this conclusion is the strong northeast-southwest regional trend of the distribution of the Peach Springs Tuff (fig. 5). To the east, where a series of ranges, particularly the Harquahala, Harcuvar, and southeastern Buckskin Mountains, also have a conspicuous northeast trend (pl. 2), very few Tertiary rocks are exposed in the intervening valleys.

It appears possible that the coarse clastics of the lower Tertiary section were derived from northeast-trending uplifts or "welts"; the axis of one such uplift may have extended from the West Riverside Mountains northeastward through the Buckskin and Rawhide Mountains. This ancestral northeastward trend in the topography would have influenced Miocene depositional patterns throughout the region.

Numerous unconformities exist within the lower part of the Tertiary section, but these are mostly local changes in depositional conditions and have not been interpreted as regionally meaningful. One impressive unconformity within the Tertiary section, which is particularly well displayed in the southern Whipple Mountains (sec. C, fig. 4), records a change from breccias, conglomerates, and lavas to limestones, sandstones, and siltstones. These sediments were deposited in relatively small basins but show locally strong discordance upon the older rocks. Tilting and faulting of the older Tertiary rocks had thus begun, at least in some areas, and local blockage of drainage was occurring. This event can be dated as generally between 20 and 17 m.y. ago, the age of underlying andesites and the overlying Peach Springs Tuff.

The Peach Springs Tuff is apparently conformable with underlying rocks at a few localities, but at most outcrops it is unconformable on a variety of sedimentary and volcanic rocks. The upper contact of the tuff and its erratic preservation indicate considerable erosion after its emplacement as well. Younger conglomerates commonly contain boulders and cobbles of the tuff, but in most areas these rocks are not well exposed. The Peach Springs does not cover sufficient area in most places in the region to provide a consistent structural datum. However, in some locations, such as Chemehuevi Valley, it is sufficiently widespread to record moderate displacement by normal faults. It is believed that faults that affect the Peach Springs are part of the important system of extensional faults that are clearly related to the Whipple Mountains detachment fault.

MIDDLE MIOCENE UNCONFORMITY

The most significant Tertiary unconformity in the Vidal-Parker region occurs at the base of the fanglomerate of Osborne Wash, a complex unit that probably spans a long interval of time. In the extreme case, sedimentary rocks younger than the Peach Springs Tuff are standing vertical and are overlain by the nearly flat lying fanglomerate. Though not everywhere spectacular, this is a consistent angular unconformity of regional importance. Age of the unconformity has not been precisely established, but the youngest rock thought to predate the unconformity is the basalt of the Mopah Range (sec. B, fig. 4), about 14.5 m.y. old. Near Parker, basalts intercalated in the lower part of the fanglomerate gave ages (table 2) from about 16.5 to

12.5 m.y. ago. General relationships suggest that the younger of these ages is probably more nearly correct. If so, this would indicate that the unconformity developed about 13 or 14 m.y. ago, an age which is a little older than that for a similar change in tectonism described south of Lake Mead by Anderson, Longwell, Armstrong, and Marvin (1972), in which volcanic rocks (Mount Davis and Patsy Mine Volcanics), highly extended and tilted, are overlain unconformably by the Muddy Creek Formation, including the Fortification Basalt Member consisting of several flows dated at about 5-11 m.y. This range of ages is close to those available for basaltic rocks of the fanglomerate of Osborne Wash in the Parker area.

Damon, Shafiquallah, and Lynch (1973) date formation of this unconformity at between 17 and 12 m.y. ago in northern Arizona; and Eberly and Stanley (1978), in a synthesis of Cenozoic stratigraphy and geologic history of southwestern Arizona, restrict formation of the unconformity to 13-12 m.y. ago. Their restriction does not seem to apply to the Vidal-Parker region where only minor block faulting occurred after about 14 m.y. ago.

WHIPPLE MOUNTAINS DETACHMENT FAULT

The most significant and spectacular Tertiary structural feature of the Vidal-Parker region is a major detachment fault (fig. 9) named for the Whipple Mountains where its relations are well exposed. Only faults of this type in the Mojave-Sonoran Belt are here referred to the Whipple Mountains detachment fault. The significance, and even the existence, of this fault has been debated for many years. Probably the first to recognize the fault was F. L. Ransome in unpublished reports for the Metropolitan Water District of California in the 1930's. He described it as an overthrust of Tertiary age, and he believed that it occurred prior to the main normal faulting of the region. Ransome's observations were later discounted by Kemnitzer (1937), who did not recognize the nature of the detachment fault and emphasized the higher angle faulting of the eastern Whipple Mountains. Terry (1972) studied the fault in detail in the eastern Whipple Mountains, but she, too, called it a thrust fault and did not recognize its involvement with rocks of Tertiary age. She did, however, suggest that the fault has regional extent. Shackelford (1976, 1980), on the basis of a thesis study in the Rawhide Mountains, identified the fault as a major Miocene gravity detachment surface, which he called the Rawhide Mountains detachment fault. Furthermore, he recognized the northeasterly transport of the allochthon and the close relation between shingling listric normal faults and the detachment surface. His description indicates a structural situation in the Rawhide Mountains nearly identical with that mapped in the Vidal-Parker region. More recently, Lingrey, Evans, and Davis (1977) described the Whipple Mountains fault as a denudational fault of Tertiary age, between 14 and 19 m.y. in age, and they indicated a northeasterly transport for the allochthon.

Geologists for the Southern Pacific Company mineral survey in 1960 mapped fairly continuous low-angle faults in the Chemehuevi, Sacramento, and Piute Mountains, Calif. (pl. 2). According to Keith Howard (U.S. Geological Survey, oral commun., 1979), however, the fault in the Piute Mountains is not the typical detachment type found farther southeast. In the present study, reconnaissance of some of these faults showed that many of them do have the characteristics of the Whipple Mountains detachment fault (pl. 2). Study of aerial photos, and limited reconnaissance, indicate that faulting of this type may also be present in the Mohave Mountains, Ariz.

Plate 2 shows the distribution, both mapped and inferred, of the Whipple Mountains detachment fault in Arizona and California. The structure probably extends into areas beyond those shown, particularly to the northwest and southeast. It has not been identified beyond the general boundaries of the Mojave-Sonoran Belt.

My interpretation of the subsurface extent of the fault is shown on plates 2 and 4. Connection of the fault from range to range beneath cover of upper Cenozoic rocks has not been proven, but characteristics, at least in the Vidal-Parker region, are so similar in different places that it is reasonable to postulate such connections. Furthermore, estimates of the amount of transport on the fault require that it extend distances at least equal to that between ranges.

Physical characteristics of the Whipple Mountains detachment fault are easily recognized in most exposures. The fault surface is normally a planar, smooth, locally polished surface, with very few abrupt changes in attitude. Multiple splays or wide gouge or breccia zones are not common. Slickensides or grooves are locally present and nearly always indicate relative northeastward motion of the upper plate—regardless of the direction of dip of the fault. Small, thin wedges of Tertiary sedimentary rocks have been observed caught along the fault between upper and lower plate metamorphic rocks. Adjacent to the fault, a finely crushed zone several meters thick is commonly present, principally in the lower plate metamorphic rocks. This material is stained dark bluish green to orange locally, and copper carbonates are present along the fault in some areas. Most of the copper and gold mines and prospects of the region are located on or near this detachment surface.

Mineralization occurs in both upper and lower plates of the fault, and deposits are found in metamorphic rocks, in Paleozoic carbonate rocks, and in volcanic and sedimentary rocks of Miocene age. Terry (1972) and Davis, Anderson, Frost, and Shackelford (1980) have described a thick mylonitized zone below the fault in the eastern Whipple Mountains. I observed similar mylonitic rock in association with the Whipple Mountains detachment fault in the Riverside and Buckskin Mountains.

The fault is rarely cut by other faults or intrusive rocks in the Vidal-Parker region. However, in the southern Riverside Mountains, rhyolite bodies were intruded along it (see map by Hamilton, 1964), and subsequently they were brecciated but not sheared off, offering a possible means for more exact dating of the latest fault movement in that area. In the western Whipple Mountains, the Chambers Well and Vidal Valley fault zones appear to offset the Whipple Mountains fault a small amount (pl. 4). In the Buckskin Mountains, offsets of several hundred feet, also on northwest-trending faults, are probable (pl. 2).

In cross sectional view (fig. 9), the fault dips away from the Whipple Mountains at about 5°. However, measured dips on the fault surface around the edge of the Whipple Mountains range from 5° to 30° and average about 20°. The reason for the discrepancy between these two figures, 5° and 20°, is not readily apparent, but it may be due to the presence of a semicircular inflection in the fault surface near the foot of the Whipple Mountains, to a tendency for the best fault plane exposures to be where dips are about 20°, or to bias introduced by measurements made on shoaling normal faults very near their juncture with the main detachment plane. In order to gain a better perspective of these problems, a regional structure contour sketch (fig. 10) was prepared of the known and postulated extensions of the fault. Only where structure contours intersect the fault is there good elevation control; elsewhere, the map is based on generalized topography over the lower plate and on estimates of elevation where the fault is buried. Crude as it is, the map shows several interesting features. The inflection mentioned previously is noticeable, particularly on the northeast side of the Whipple Mountains. Steeper than average dips are also suggested by the contours in the Chemehuevi, Mohave, and Rawhide Mountains. These steeper gradients appear to face the Colorado River, and locally the Bill Williams River, and together with the fractured nature of the upper plate must have strongly influenced the early courses of the rivers. The map also suggests the interplay of two structural trends, northeast-southwest oriented uplifts, and the subsequent local modification of these by northwest-trending faults. No regional trend in elevation of the fault surface is evident. Detailed regional study of the fault is needed for closer definition, but it is clear that development of present topography was closely controlled by the Whipple Mountains detachment fault and associated structure and lithology.

Several northeast-trending troughs are present in the detachment fault plane. One of the most notable is in the Riverside Mountains (pls. 1, 4) where such a trough contains Tertiary rocks of the upper plate striking northwest and dipping southwest at angles as high as 80°. This attitude is maintained from one edge of the trough to the other, which indicates that the rocks were transported into the trough by the detachment fault. This trough, or one adjacent and parallel to it, may extend northeastward up the Colorado River Valley as far as the Bill Williams River (fig. 10). It was suggested previously that in some areas coarse Tertiary deposits probably accumulated next to northeast-trending ridges in the basement rocks. These ridges seem to have strongly influenced the shape of the fault plane in some areas. Other northeast-trending basins, such as Mc Mullen and Butler Valleys, lying between the Buckskin, Harcuvar, and Harquahala Mountains (pl. 2), are suspected as additional areas where the detachment fault is present but buried in most places. Terry (1972) also suggested this possibility.

In the Vidal-Parker region, there are few exceptions to the persistent northwest strike and southwest dip of the Tertiary rocks in the upper plate of the fault. To the east, however, in the Buckskin and Rawhide Mountains, attitude of the rocks becomes locally more variable, although regionally the northwest-trending structural grain of faulting and southwestward rotation of beds persists (Lucchitta and Suneson, 1977a; Lasky and Webber, 1949; Otton, 1977). In one narrow northeast-trending trough located northwest of Clara Peak in the Buckskin Mountains (pl. 2), the Tertiary rocks strike parallel to the trough and dip to the southeast. Shackelford (1980) reported that in the Rawhide Mountains the tectonic transport direction of the upper plate was dominantly northeastward, but he added that the direction was locally controlled by configuration of the basement structure. Perhaps toward the northeast margin of the Mojave-Sonoran Belt, structural complexities in the basement rocks and lessening cover of Tertiary rocks favored more diverse local movements of the allochthon.

REGIONAL IMPLICATIONS

In this report the Whipple Mountains detachment fault has been documented by mapping in the Whipple, Buckskin, and Riverside Mountains. In addition, reconnaissance has confirmed its presence in the Chemehuevi and the northeastern part of the Sacramento

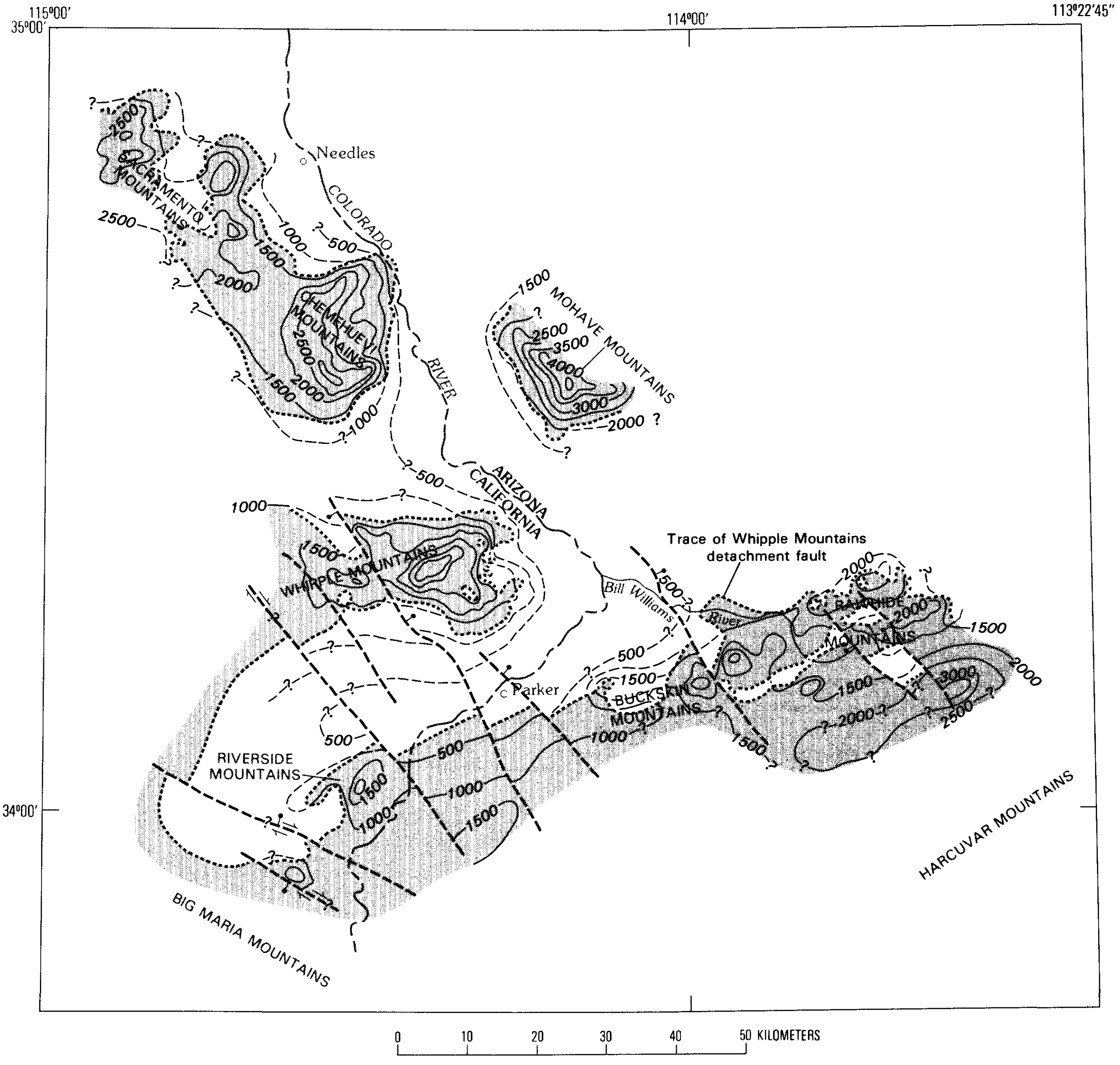

FIGURE 10.—Structure contour sketch map of the Whipple Mountains detachment fault. Shaded areas, lower plate (mapped and inferred); dotted line, trace of detachment fault. Heavy dashed lines, faults; bar and ball on downthrown side; arrows show direction of lateral movement, queried where uncertain. Contour interval 500 ft; contours dashed where fault is beneath surface, queried where control is especially poor.

Mountains. Studies by others indicate that a similar structure is also present in the Rawhide Mountains, Ariz., and probably in the valleys between the Harcuvar and Harquahala Mountains. It seems reasonable to conclude, therefore, that a detachment fault, possibly a nearly continuous surface, is present in an area about 100 km wide by at least 150 km long (fig. 9).

The faulting of the Whipple Mountains detachment type is similar in many ways to Tertiary low-angle faults mapped elsewhere in the Basin and Range province, but particularly to those in the Walker Lane Belt (as defined here, p. 4) to the northwest, and in the Texas lineament (Albritton and Smith, 1957) to the southeast in Arizona. Barosh (1969) called the southwestern edge of these belts the Mojave lineament and emphasized its great length and strike-slip faulting character. Albritton and Smith (1957), in their review of the history of the lineament, pointed out that Kelley (1955) mentioned the Texas lineament as one of the most prominent in North America. Kelley also implied that the Walker Lane and Texas lineaments should be connected, a view I share. Most authors except Kelley and Barosh had envisioned the Texas lineament as bending westward to join the Transverse Ranges of Southern California. The physiography and structure of the eastern Mojave Desert seem to argue against such an interpretation. Connecting the Walker Lane and Texas lineament provides an effective eastward terminus for the major left lateral faults of southern California—the Garlock fault and those of the eastern Transverse Ranges. Connecting the Texas lineament and the Transverse Range structure has led some authors (Albritton and Smith, 1957) to imply that the zone is one of left-lateral strike-slip; whereas, evidence in hand strongly suggests that in Arizona and southeasternmost California right-lateral, probably oblique slip, at least in Tertiary time, is the most likely style of displacement.

I believe that major detachment faulting of Tertiary age is an important feature of the structural corridor from southeastern Arizona to northwestern Nevada. Faulting of this type, not everywhere proven to be Tertiary in age, has been described in the Tucson area (Drewes, 1973; Davis, 1975; Thorman, 1977), at Old Dad Mountain (Dunne, 1977), and in the Kingston Range, Calif. (Hewett, 1956), in southeastern Nevada (Anderson, 1971), in the Death Valley region (Noble, 1941; Hunt and Mabey, 1966; Wright and Troxel, 1973; Wright and others, 1974), and in the Yerington, Nev., area (Proffett, 1977). Armstrong (1972) has summarized evidence for Tertiary low-angle denudational-type faulting in the Sevier orogenic belt area of eastern Nevada and western Utah. In that region the evidence for Tertiary age of the low-angle faulting is not always as clear as it is in the Mojave-Sonoran Belt. Nevertheless, a number of well-documented cases have been described. Many other areas, such as the Kingston Range, Calif., for example, lack Tertiary rocks, so that determination of the age of the faults is difficult, but the listric or flattening normal faults in the upper plate and their mergence into a single sharp plane of dislocation, together with steeply rotated beds in the fault blocks, are features that serve to characterize and identify the structure.

Perhaps the most striking structures similar to the Whipple Mountains detachment fault are the turtlebacks of the Death Valley area (Curry, 1938), which have been interpreted by some authors (Hunt and Mabey, 1966) as part of a continuous fault, the Amargosa thrust. A number of different mechanisms have been proposed for formation of the turtlebacks or Amargosa thrust, but I prefer the interpretation of Wright, Otton, and Troxel (1974), which relates the faulting to extensional tectonics. Specifically, they believe the individual turtlebacks to be giant fault mullions; they conceived of the surfaces developing along preexisting planes of weakness, closely followed by deposition of the Tertiary rocks and by pulling apart of the Death Valley area in a northwest-southeast direction, giving impetus to continued gliding on the fault surfaces. This structural development could apply to the Whipple Mountains detachment fault, except that major movement occurred after most of the Tertiary rocks were deposited and the direction of extension was at right angles (northeast-southwest) to that in the Death Valley area; significantly, there was no development in the Vidal-Parker region of deep structural basins, and, therefore, no driving force for continued downslope movement on the Whipple Mountains fault.

ORIGIN OF WHIPPLE MOUNTAINS DETACHMENT FAULT AND REGIONAL EXTENSION

Before speculating on tectonic reasons for development of the fault, it is well to summarize some pertinent facts. First, abundant stratigraphic and structural evidence restricts the major movement on the fault to a period of less than a 5 m.y. range—younger than about 18 m.y., the approximate age of the Peach Springs Tuff, and older than about 13 m.y., the probable oldest age of basalt of the fanglomerate of Osborne Wash, which is not cut by the fault. Basalt of the Mopah Range, dated at 14.5 m.y. old, probably is involved in the faulting, but this has not been proven. The fact that a few of the major faults that cut the younger Tertiary rocks also displace the Whipple Mountains detachment fault suggests that movement on the latter may have been completed even earlier. Shackelford (1976) gave a maximum age of 15.9 m.y. for the deformation in the Rawhide Mountains, and Lingrey, Evans, and Davis (1977) assigned an age of between 14 and 19 m.y. for the Whipple Mountains fault. All the available evidence, therefore, suggests that most, if not all, of the movement was accomplished in a few million years or less.

Fission-track studies (Dokka and Lingrey, 1979) on metamorphic rocks from the eastern Whipple Mountains show that rapid cooling occurred there in the period between about 20–18 m.y. ago. As they pointed out, this agrees well with the age of volcanism in that area, but since these same volcanic rocks are displaced by the Whipple Mountains detachment fault, that faulting appears to be a somewhat younger event.

Slickensides and grooves in the fault surface trend rather consistently northeast-southwest, from the Rawhide Mountains to the Riverside Mountains. Low-angle normal faults in the upper plate are also fairly consistent, trending at right angles to the direction of transport and dipping northeast. Thus, the dominant apparent direction of movement of the allochthon was to the northeast in an area at least 100 km wide. The actual amount of displacement was considered by Lingrey, Evans, and Davis (1977) to be at least 15 km, based on dissimilarity of upper and lower plate basement rock in that distance in the Whipple Mountains. Comparison of metamorphic rocks in the two plates in the eastern and western Whipple Mountains suggests that the amount of displacement probably exceeds 20 km; metamorphic rocks similar to those in the upper plate in the northeastern Whipple Mountains do not appear in the lower plate east of the Chambers Well area (pl. 1). If the Paleozoic rocks in the upper plate northeast of Parker came from similar rocks in the lower plate in the Riverside Mountains area, the transport distance may have been as much as 35 or 40 km.

Apparently, at the original location of the upper plate, prior to faulting, exposures of rocks typical of the lower plate in the eastern Whipple Mountains were very rare. The evidence of this lack of exposure is the scarcity of clasts of lower plate rocks in the Tertiary breccias in the eastern Whipple Mountains. Davis, Anderson, Frost, and Shackelford (1980, p. 94–95) emphasized the presence of a few clasts of the lower plate mylonite—or banded gneiss—in the Tertiary section of the eastern Whipple Mountains. In my experience, such occurrences are very rare, and one is impressed by the extreme scarcity of such material. Some occurrences (Davis and others, 1980) of lower plate gneiss cobbles in the Tertiary section may well be in rocks high in the section, quite possibly in units that should properly be assigned to the fanglomerate of Osborne Wash. (See pl. 1.)

Davis, Anderson, Frost, and Shackelford (1980, p. 111) have offered evidence that the mylonite zone was developed well before the Whipple Mountains detachment faulting. They have obtained early to middle Tertiary K-Ar ages (oral commun., 1980) on the mylonitic gneiss and have associated the zone with intrusive rocks beneath the fault; they also pointed out that in the west-central Whipple Mountains the detachment fault diverges from what they call the "mylonitic front." In addition, mineral lineations in the lower plate gneiss are commonly not parallel with the detachment surface. The evidence for two separate tectonic events, mylonitization and detachment faulting, is compelling, yet the close spatial association of the two features is puzzling, as is the obvious active tectonism indicated by the lithology of the Miocene rocks. I believe that the close spatial association of the detachment fault with the mylonitization is the result of a strong tendency for the shearing to occur near the top of the competent mylonitized rocks. I have seen no good evidence for significant post-detachment doming. Radial dips in Tertiary rocks away from structural highs are nonexistent in the Vidal-Parker region, and there is no indication that radial faulting occurred. In the Riverside Mountains, however, Tertiary breccias do contain abundant Paleozoic rock clasts typical of the lower plate immediately to the east. This could mean that the amount of effective transport lessened close to the southwest edge of the Mojave-Sonoran Belt.

Thus, available evidence points strongly to a fairly rapid and directionally consistent extension of as much as 40 km in a period probably occurring mostly between about 17 and 14 m.y. ago. These figures yield a rate of movement of a little over 1 cm per year, a figure consistent with estimates (Stewart, 1971, p. 1036) for Great Basin extensional rates.

The mechanism and driving forces of the Whipple Mountains detachment fault are not well understood. Its wide distribution and consistently northwest-trending upper plate structure, as well as the lack of a regional northeasterly slope, all argue strongly against a pure gravitational origin. Transport between strike-slip faults and volume compensation by concurrent plutonism, as envisioned by Anderson (1971, p. 57), is an appealing explanation, but important northeast-trending strike-slip structures or sizeable Tertiary intrusives have not been recognized in the area.

As mentioned earlier, possible northeast-trending "welts" are a feature of at least part of the region. These may be a clue that older northeast-trending zones of weakness may have existed, and they probably record a regional Tertiary thermal event that brought laminar flow fairly close to the surface. This concept of a plastically extending substratum, as suggested by Hamilton and Myers (1966), Anderson (1971, p. 56), and Stewart (1971, p. 1038), is an attractive mechanism for the deformation.

The overprint of Tertiary volcanism, none of it voluminous in this area, may also have been localized by the welts. The shift to bimodal rhyolite-basalt volcanism so often cited (Christiansen and Lipman, 1972) as accompanying the beginning of basin-and-range faulting, seems reasonably coincident with faulting in the Vidal-Parker region, but contrary to events in most of the Basin and Range province, this faulting ended as abruptly as it began. It is interesting to note that the virtual cessation of extension and major faulting in the Vidal-Parker region is essentially synchronous with the generally accepted age of inception of the present San Andreas fault, about 14 m.y. ago. This is another strong indication that the structure in the region is related to plate tectonics and underflow of the continental margin by the Pacific plate.

EARLY END OF FAULTING

The low intensity of Pliocene and virtual lack of Pleistocene faulting, in coincidence with a near absence of even low-level seismicity, make this region unique in the Basin and Range province. Until we better understand the cause of presently active basin-and-range faulting elsewhere, it is difficult to explain its absence here. No obvious differences in the geologic history can be called upon to explain the rather abrupt early end to structural movements. The region in which this quiescence is best displayed seems to be generally coincident with part of the Mojave-Sonoran Belt, which in turn is geophysically characterized by rather subdued anomalies. The Belt can be viewed geophysically as a relatively quiet bench between the foot of a regional northwest-trending gravity gradient (pl. 2) and the northwest trends associated with the San Andreas and older structures. According to seismic refraction data (see p. 23), the Vidal-Parker region is only slightly anomalous; the crust is probably a little thinner (26–27 km) than in most of the Basin and Range area, and the upper mantle velocity (about 8 km/s) is perhaps a little higher than average for the province. Perhaps a partial explanation can be found in the possibility that the boundary between plastic and brittle crustal failure may lie at a shallower depth than elsewhere in the Basin and Range, and therefore that during the last 10 m.y. or so, extension has taken place almost entirely by plastic flow at depth.

PLIOCENE-PLEISTOCENE TECTONICS

Faults and lineaments of Pliocene and possibly early Pleistocene age in the Vidal-Parker region are listed in table 5. Available information indicates that faulting of this age becomes a little more intense near the northeast edge of the Vidal-Parker region and increases northeastward toward the margin of the Mojave-Sonoran Belt. Northwest-trending faults along the Bill Williams River and in the Buckskin Mountains cut basaltic rocks and some of the fanglomerate of Osborne Wash. Several of the northwest-trending faults in the northeasternmost Whipple Mountains produce tilting of as much as 35° in the fanglomerate (pls. 1, 4). Farther east, about 10 km above the mouth of the Bill Williams River, another fault displaces basalt of the Osborne at least 100 m vertically. Examination of aerial photos and discussion with Ivo Lucchitta and Neil Suneson of the U.S. Geological Survey indicate that significant faulting of probable Pliocene volcanic rocks and sediments continues to occur to the northeast in the Bill Williams Mountains area. As mentioned previously, similar faults cut alluvium of probable Quaternary age a few miles northeast of Topock, Ariz. (pl. 2).

The youngest rocks known with certainty to be faulted at the surface in the Vidal-Parker region are the marine and supra-littoral equivalents of the Bouse Formation (age about 5 m.y.). Several faults with only a few meters of displacement in sandy Bouse Formation were mapped (Dickey and others, 1980; Carr and others, 1980) along the south flank of the Whipple Mountains. At the north end of Mesquite Mountain, along Bouse Wash, is a fault (pl. 1) with at least 3 m of offset in the Bouse. It is close to the only steep linear gravity gradient in the Vidal-Parker region. Another fault offsetting the Bouse is present on the northwest side of Mesquite Mountain. A zone of small faults occurs in sandy fanglomerate in the Parker NW. quadrangle (Dickey and others, 1980). Rocks cut by these faults are mapped as fanglomerate of Osborne Wash, but it is possible that they are coarser grained subaerial time equivalents of the Bouse Formation. Individual faults in the zone are generally less than 300 m long and have less than 5 m of vertical offset. On this same trend, Metzger and Loeltz (1973, pl. 1) showed a buried fault in the Bouse 2 km south of Parker. The fault or fold is based on drill hole information and is shown as having about 15 m of offset in the Bouse Formation-fanglomerate of Osborne Wash contact.

Several low-angle faults, judged to be slump features, were observed in fine-grained sediments of the Bouse, particularly in the areas between the Whipple Mountains and Lake Havasu City. Because of the limited exposures of the Bouse, other small faults may well be present, but buried.

Several strong photo lineaments, some of which are definitely faults, occur in the old alluvium (unit QTa, pl. 1). In addition, there are a number of small faults that do not show up on aerial photos. These features are summarized in table 5, and most are shown on plate 1. None of the faults in table 5 are considered to cut alluvium less than about 1 m.y. in age, and most are probably latest Pliocene in age.

The youngest faults of the region are difficult to interpret. There is no evidence that any of them represent more than minor adjustments, mostly along preexisting structures. The only such faults that constitute any sort of continuous zone are those in a north-trending belt on the south side of the Whipple Mountains, and nearly all of these are older than the old alluvium (loc. 4, table 5). They could represent shears

TABLE 5.—*Faults and photo lineaments in old alluvium of the Vidal-Parker region*

Location	Strike	Dip	Displacement	Length	Remarks
1. Unsurveyed NW1/4 sec. 5, T. 2 N., R. 23 E., between Savahia and Pyramid Peaks.	N. 45° W.	60° NE.	1 m	About 600 m.	Very slight topographic expression.
2. Unsurveyed sec. 8, T. 9 N., R. 17 W., upper Osborne Wash area.	N. 40° W.	Unknown	Unknown	About 600 m.	Slight topographic expression, distinct color lineation.
3. NE1/4 sec. 24, T. 2 N., R. 23 E. About 0.2 km NE of jeep trail between Savahia Peak and Chambers Well road.	Northeast	55° NW.	0.5 m	Unknown	Cuts caliche at base of old alluvium (unit QTa, pl. 1).
4. Unsurveyed: sec. 5, T. 1 N., R. 25 E., and sec. 31 and 32, T. 2 N., R. 25 E., in aqueduct cut and north and south of it.	Northerly	65° to vertical.	Mostly 1 m; one at least 5 m.	As much as 300 m.	Zone of small short faults about 2 km long, a few of which cut beds possibly as young as the old alluvium.
5. Near north edge of unsurveyed sec. 30, T. 2 N., R. 25 E.	N. 10° W.	80° NE.	At least 2 m.	At least 100 m.	Same zone that cuts sandy phase of Bouse Formation.
6. NW1/4 sec. 2, T. 2 N., R. 22 E., about 400 m east of U.S. Highway 95.	N. 15° W.	Probably eastward.	Unknown	At least 100 m.	Very slight topographic scarp.
7. Unsurveyed E1/2 sec. 20 T. 2 N., R. 22 E.	North and northwest.	Unknown	Unknown	About 300 m.	Not exposed, but probably displaces caliche cemented old alluvium.
8. 5-7 km N. 70° W. of Whipple Well, north side Whipple Mountains.	N. 45° W. to N. 80° W.	Unknown	Unknown	1.5 km	Noticeable photo lineament.
9. Sec. 4, T. 2 S., R. 21 E., near middle of Rice Valley.	N. 50° W.	Unknown	Unknown	2 km	Noticeable photo lineament; possible ground water barrier.
10. Sec. 25, T. 2 N., R. 22 E. and sec. 30, T. 2 N., R. 23 E., north-northwest of Vidal Junction.	N. 80° W.	Unknown	Unknown	1.7 km	Weak, but distinct lineation.
11. Sec. 18, T. 1 S., R. 24 E.; south-southeast of Vidal.	N. 65° W.	Unknown	Unknown	1 km	Noticeable photo lineament.
12. Near north end of valley between Mopah Range and Turtle Mountains, about 3 km west of Mopah Peaks.	North-northwest.	Unknown	Unknown	Unknown	Cuts old alluvium (QTa). Found in reconnaissance for Southern California Edison Company by Woodward-McNeill, Inc.

in the surficial materials caused by right-lateral stresses on nearby northwest-trending faults in the bedrock. As such they might be considered as incipient basin-and-range faults that never developed further.

If there is significant structural displacement of the Bouse Formation, it is buried beneath the alluvium. All evidence, however, indicates that the Bouse has not been greatly disturbed by structural movements in the Vidal-Parker region, although Lucchitta (1979) demonstrated differential uplift of the Bouse about 50 km to the north, along the margin of the Mojave-Sonoran Belt. There is a suggestion of some warping of the Bouse, particularly on the north side of the Whipple Mountains, but even most of this could be explained by initial dips. However, as the Bouse is more than 500 ft below sea level beneath the Colorado River flood plain near the south edge of the mapped area (pl. 1; Metzger and Loeltz, 1973, pl. 1), it seems likely that some downwarping and faulting has occurred in that part of the area at least. Between Parker and the Big Maria Mountains, the Colorado River now maintains a course at the west side of the wide flood plain of Parker Valley, which suggests a possible slight regional tilt to the west in Holocene time.

SUMMARY OF STRUCTURAL HISTORY

Geologic studies in the Vidal-Parker region permit a tentative interpretation of some of the Mesozoic and Cenozoic structural events.

The age, or even the existence, of Mesozoic faulting in this region has not been proven; rocks of Mesozoic age are involved in low-angle normal and thrust faulting along the southwest side of the area, but the maximum age of this faulting has not been determined. Possible influence on later structural events suggests there may have been an early conjugate fault system of northeast and northwest trends.

Intrusion of small granitic batholiths took place in Late Cretaceous time. Margins of these intrusives and adjacent Paleozoic and Mesozoic sedimentary rocks underwent varying degrees of dynamic metamorphism. This metamorphic event probably ended about 60 m.y. ago and was followed by uplift and erosion.

In middle Tertiary time it is postulated that magmatism in the crust caused tumescence or welts that tended to localize on preexisting northeasterly trending structural zones of weakness, or, because of tensional stress, between offset ends of concurrently developing northwest-trending strike-slip faults. Core complex metamorphism and intrusive activity was accompanied by large-scale mylonitization. The welts or uplifts, though fairly gentle, probably occurred rapidly enough to shed considerable debris, which accumulated on the flanks as conglomerate, breccia, and megabreccia. In Miocene time, volcanism, mostly andesitic and rhyodacitic, occurred at scattered centers possibly related to these magmatic uplifts.

About 17 m.y. ago rapid extension began in the Mojave-Sonoran Belt, possibly driven by southwestward movement of the lower crust. As much as 40 km of extension may have occurred in the Belt in a few million years. The extension resulted in stretching and thinning of the crust and formation of a regional low-angle shear or detachment fault at fairly shallow depth, which was probably controlled by the abrupt upper limit of mylonitized rocks. This shearing off was accompanied by synchronous northwest-trending low- to moderate-angle normal faults and attendant rotation of fault blocks. Abruptly, about 14 m.y. ago, this style of structural development ceased, perhaps in response to changes in regional stress brought about by the beginning of transform movement on the initial stages of the San Andreas fault system.

Only minor dip-slip and right-lateral slip occurred in late Miocene and Pliocene time on a few of the northwest-trending faults. Toward the northeast and southwest edges of the region, these faults had more and perhaps slightly younger displacement. Eruption of basaltic and minor rhyolitic rocks began about 14 m.y. ago and continued sporadically until about 6 m.y. ago. Very small normal faults, mostly high-angle and having north and northwest trends, developed locally in late Pliocene time. Slight regional and local warping has been the only structural disturbance in the Pleistocene.

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