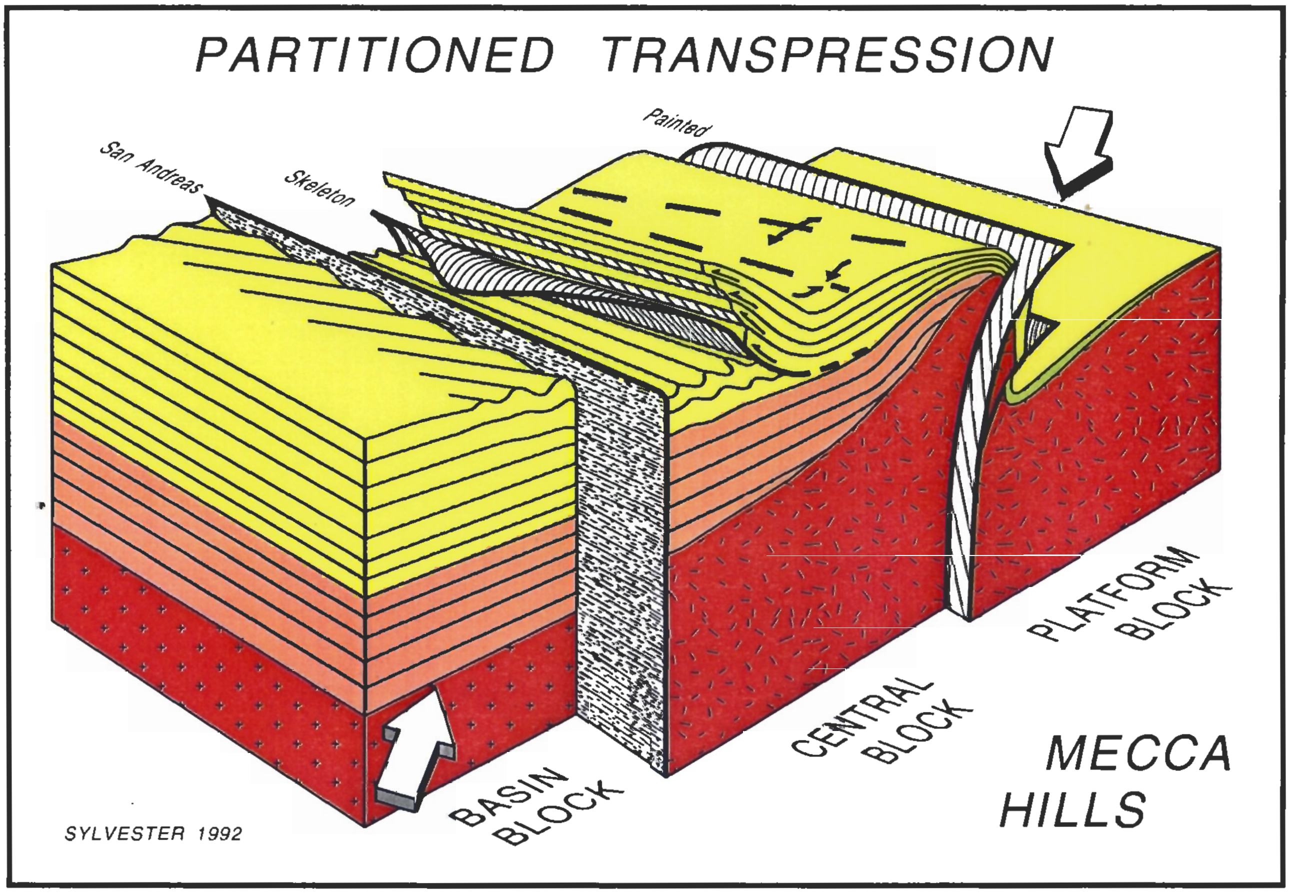
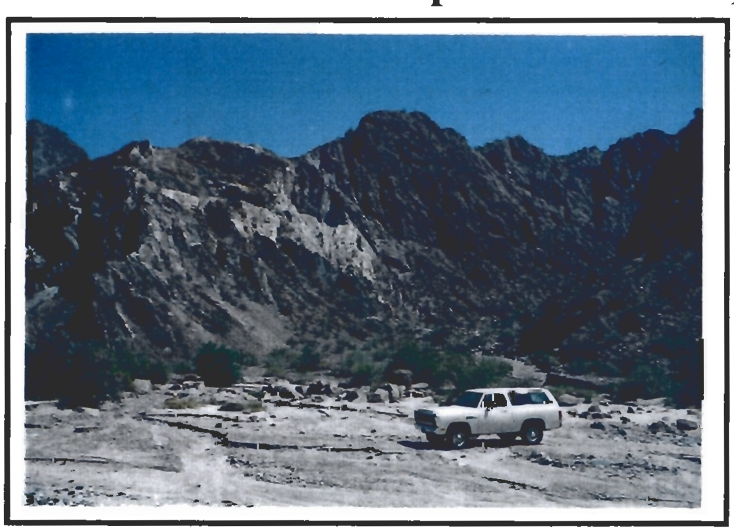
Rifting, Transpression, and Neotectonics in the Central Mecca Hills, Salton Trough



Pacific Section SEPM Fall Field Trip Guidebook
September 25-26, 1999



FIELD TRIP LEADER

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Santa Barbara

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Rifting, Transpression, and Neotectonics in the Central Mecca Hills, Salton Trough

by

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Pacific Section SEPM Officers – 1999

RIFTING, TRANSPRESSION, AND NEOTECTONICS IN THE CENTRAL MECCA HILLS, SALTON TROUGH, CALIFORNIA

Field Trip Guidebook for the SEPM Fall Field Trip, 1999

Arthur Gibbs Sylvester, Field Trip Leader
Department of Geological Sciences
University of California, Santa Barbara

Contents

Cover Illustration. Schematic block diagram of partitioned transpression in central Mecca Hills, view from south to north. Main faults, San Andreas, Skeleton (Canyon), and Painted (Canyon), separate three crustal blocks: basin, central, and platform. Arrows indicate principal direction of shortening, oblique to the main faults. Shortening accommodated by folding, by out-of-the-syncline thrusting on Skeleton (Canyon) fault, and by oblique reverse-slip on Painted (Canyon) fault. Horizontal shear accommodated by right slip on San Andreas fault and by oblique reverse-slip on Painted (Canyon) fault. Presented by Sylvester (1992). **Inset**. Painted Canyon fault in northeast wall of Painted Canyon. Fault dips 60° toward vehicle from skyline notch, and separates dark gray Precambrian gneiss cut by white granite dike in footwall from red brown, late Miocene Mecca Formation that dips about 45° toward right (southwest). Initially a normal fault, now reactivated as an oblique, reverse right-slip fault.

Logistical Preface to the Field Excursion

A few logistical remarks pertaining to entry in the Mecca Hills are worth emphasizing. The region is part of the Mojave National Preserve with all relevant regulations and policies pertaining to camping, rock and plant collecting, and motorized vehicles which are permitted only on designated roads. Parking is permitted only within 50 m of the edges of those roads. Visitors should be aware of the hazards associated with flash floods, washed out roads, soft sand, off-road vehicles even on established roads, thieves, and shooters. Despite what you may see, dumping and littering are prohibited anywhere in the Mecca Hills. Temperatures soar to more than 104°F (40°) in late spring, summer, and early fall. Two plants, the smoke tree and the desert holly, are protected by law and must not be disturbed. Rattlesnakes and scorpions are among the endemic fauna and should be respected. Nearly all aspects of the general geology can be seen adequately from the canyon floor or can be reached by short hikes up side canyons. Due caution should be exercised when climbing the friable rocks of the canyon walls. In the courses of many little canyons are abrupt, vertical dry falls, around most of which are no detours.

The information contained in this book is correct to the best of the author's knowledge at the date of publication. The author, SEPM, and the University of California assume no liability for accidents, injury, or any losses by individuals or groups using this guidebook.

Rifting, Transpression, and Neotectonics in the Central Mecca Hills, Salton Trough, California

by Arthur Gibbs Sylvester

Introduction

Salton Trough is the northern, landward extension of the Gulf of California, which is over 1000 km long and up to 225 km wide (Fig. 1). The Colorado River enters the Gulf from its eastern side near Yuma, Arizona, forming a large delta cone that subdivides the trough into the nonmarine part to the north and the tidal-influenced delta and salinas in Mexico to the south. The delta blocks entry of marine waters of the Gulf into Salton Trough. In fact throughout its history, Salton Trough has experienced only one marine incursion - in late Miocene/early Pliocene time - all other sediment in the basin is lacustrine, fluvial, and alluvial.

The Salton Trough was known as the Salton Sink before the Colorado River flowed uncontrolled into it in 1905 and formed the Salton Sea. Most of it was desolate, especially in hot, dry summers. It is still desolate today, but certainly not desolated, it is still miserably hot in summer, but much more humid. On some summer days its towns are the hottest in the nation, even hotter than Death Valley.

Physiographically the Salton Trough is separated into the Coachella and Imperial valleys (Figs. 2, 3). Coachella Valley is only 10-15 km wide, bounded by high, northwest-trending mountains of crystalline bedrock. Low hills of deformed Neogene strata are aligned along active faults in the basin. Both valleys are important agricultural areas that require abundant irrigation water supplied mostly by aqueduct from the Colorado River. Aligned clumps of vegetation, especially native palm trees, mark traces of the San Andreas fault in Coachella Valley.

The second lowest point (- 72.3 m) in the United States is in the trough, beneath the Salton Sea; at its north end are the two highest mountain peaks in southern

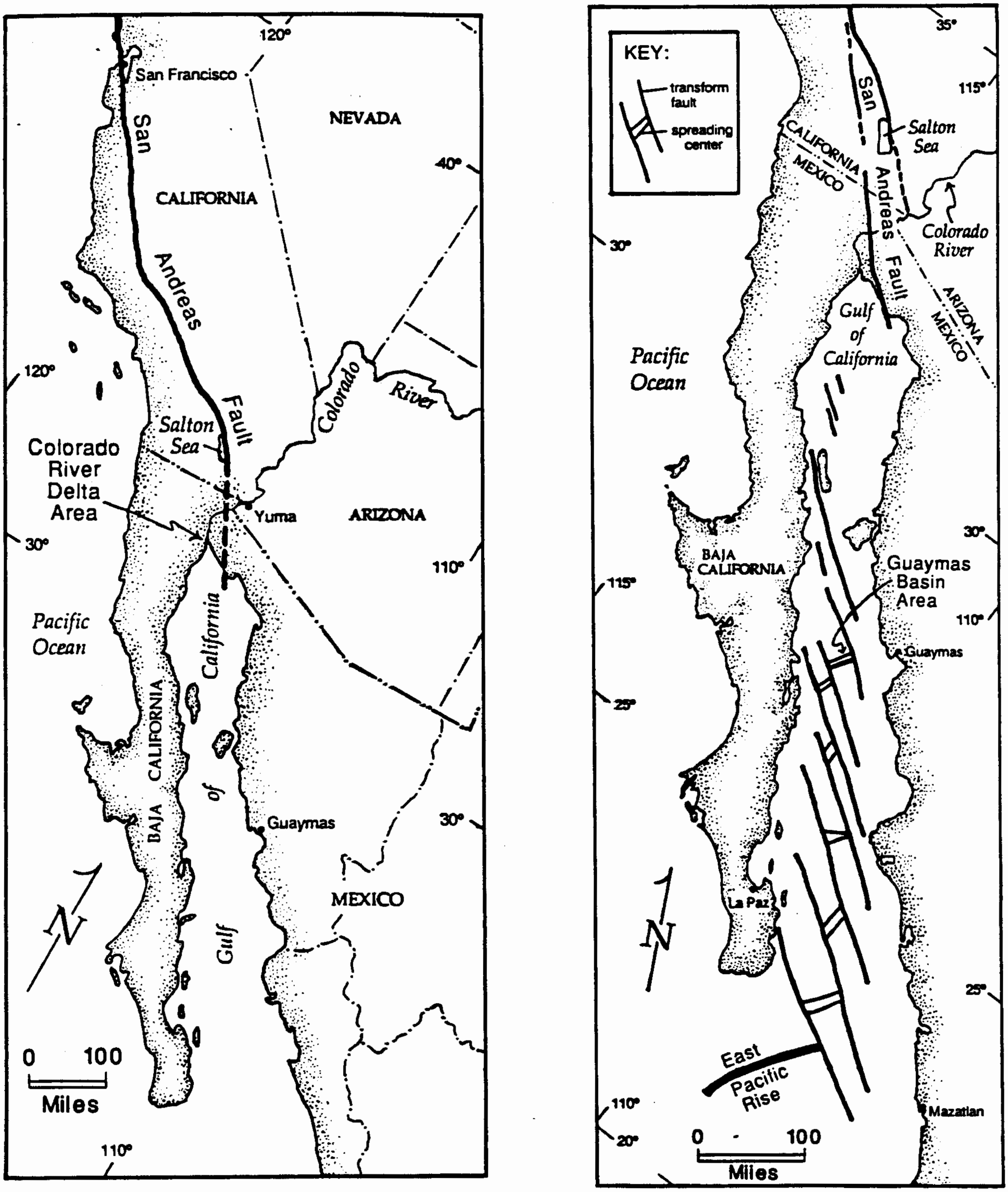


Fig. 1. Location of Gulf of California, Salton Sea, San Andreas fault zone, Colorado River, Colorado River delta, and Gulf of California spreading centers (From Schmidt, 1990).

Fig. 2. Oblique satellite image toward northeast of Salton Trough with Coachella and Imperial Valleys, Salton Sea, Mecca Hills, Joshua Tree National Park, and the Colorado River.

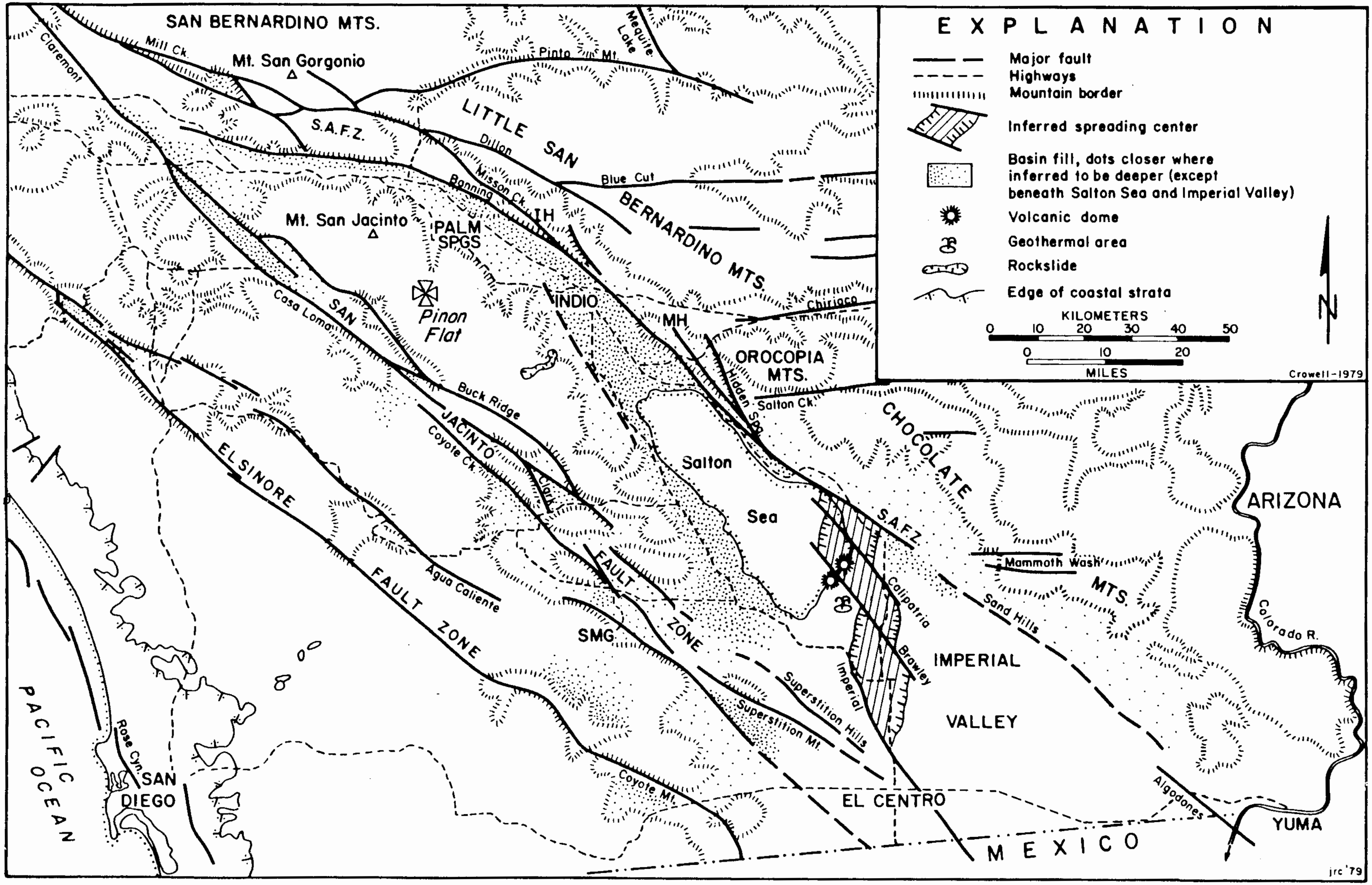


Fig. 3. Diagrammatic fault map of central Peninsular Ranges and Salton Trough region, with major faults of San Andreas system near their juncture with the divergent plate boundary in Salton Trough. Basin fill is stippled; line pattern southeast of Salton Sea is inferred active spreading centers in the Brawley seismic zone. Abbreviations: IH, Indio Hills; MH, Mecca Hills; SMG, Split Mountain Gorge (From Crowell and Sylvester, 1979).

California: Mt. San Jacinto (3324 m) and Mt. San Gorgonio (3539 m). The Whitewater River, which drains a large part of the San Bernardino Mountains, enters the north end of the basin in San Gorgonio Pass near Palm Springs. Strong winds blow through the pass across the Whitewater River alluvial fan at the head of Coachella Valley, and picking up sand and dust into the trough that are deposited in dunes mainly in the North Palm Spring area between Cabazon and Indio. The Algodones dunes are another extensive dune field in Salton Trough near Yuma.

Hydrocarbons have not been found in Salton Trough owing primarily to the lack of source rocks, but the Salton Sea geothermal field at the south end of the Salton Sea supplies about ten percent of San Diego's cravings for electric power. Wind machines at the north end of the trough produce adequate energy to satisfy the electric power demands of all the communities and casinos in the trough.

Plate Tectonic Overview

Salton Trough is the youngest of California's several Tertiary basins. It began to form about 16 my ago in mid Miocene time by crustal extension when the Pacific plate began its attempt to chip off and kidnap a long slice of the North American plate. Before the Pacific plate accomplished that dastardly deed, however, the North American crust above it extended greatly along high-angle normal faults and low-angle detachment faults, baring the top of the subducted Farallon plate beneath in tectonic windows, and giving rise to the proto Salton basin. Fragments of those faults are locally exposed in the bounding mountains as are scraps of 15 Ma- old andesite flows and interstratified alluvial and fluvial strata deposited during that extension.

Between 5 my and 4 my, the Pacific plate succeeded in its capture of a great sliver of the North American plate, consisting of all of continental Alta and Baja California that now lies between San Francisco and La Paz, and west of the present San Andreas fault (Fig. 1). South of the Transverse Ranges the plate boundary jumped eastward into the proto Salton Trough and Gulf of California where it found thinned crust and some major, high-angle faults that it could usurp east of the tough crustal slab consisting of Mesozoic magmatic arc rocks of the southern California batholith. In the Gulf the new boundary was a series of spreading ridges and transforms that connected the East Pacific Rise at the mouth of the Gulf to the San Andreas transform that extended southward from central California (Fig. 1).

Judging from seismic refraction data (Fuis et al., 1982), Salton Trough was an asymmetric basin with deep accumulation centers in its southwest corner near El Centro and its northeast margin beneath the present hamlet of Mecca. Judging from interpretations of gravity data, depth to basement beneath the trough varies greatly from 2150 m in northern Coachella Valley to 6800 m near the Mexican border. Stepover basins formed above spreading ridge segments between short transform faults in the Gulf in right shear.

The single marine incursion occurred in late Miocene - early Pliocene time, when the Imperial Shale and related turbidite and shallow marine and beach facies strata were deposited (Fig. 4). The presence of battered Cretaceous forams prove that the bulk of the basin's sediment was derived from the Mancos Shale in Utah and Colorado and carried to the basin by the Colorado River during Pliocene and Pleistocene time. At that time it flowed directly into the basin, forming thereby fresh or brackish lakes even larger and deeper than the present Salton Sea. During the past 1000 years, ancient lakes repeatedly filled Salton Trough to a highstand level of about 12 to 13 m above mean sea level. The most recent highstand was in 1663 ± 22 A.D. (Waters, 1983; Sieh and Williams, 1990); the highest shoreline is well preserved like a bathtub ring near sea level around the basin, and is reckoned to be 37,000 yrs old. The Holocene lakes are known collectively as Lake Cahuilla.

Around the margin of the basin, the lacustrine strata interfinger with alluvial fan, fluvial, braided stream, fan delta, landslide, and eolian deposits derived from the bounding mountains.

The Bounding Mountain Ranges

Salton Trough separates two physiographic provinces that differ greatly in age and rock types. Along the northeast side are the Little San Bernardino, Orocopia, and Chocolate Mountains. Rocks in the Little San Bernardino and Chocolate Mountains represent the North American plate and consist of Late Proterozoic gneiss, migmatite, anorthosite and granitic intrusions, Mesozoic granitic rocks of Sierra Nevada batholithic kindred, and Miocene (27-23 my) rhyolitic hypabyssal

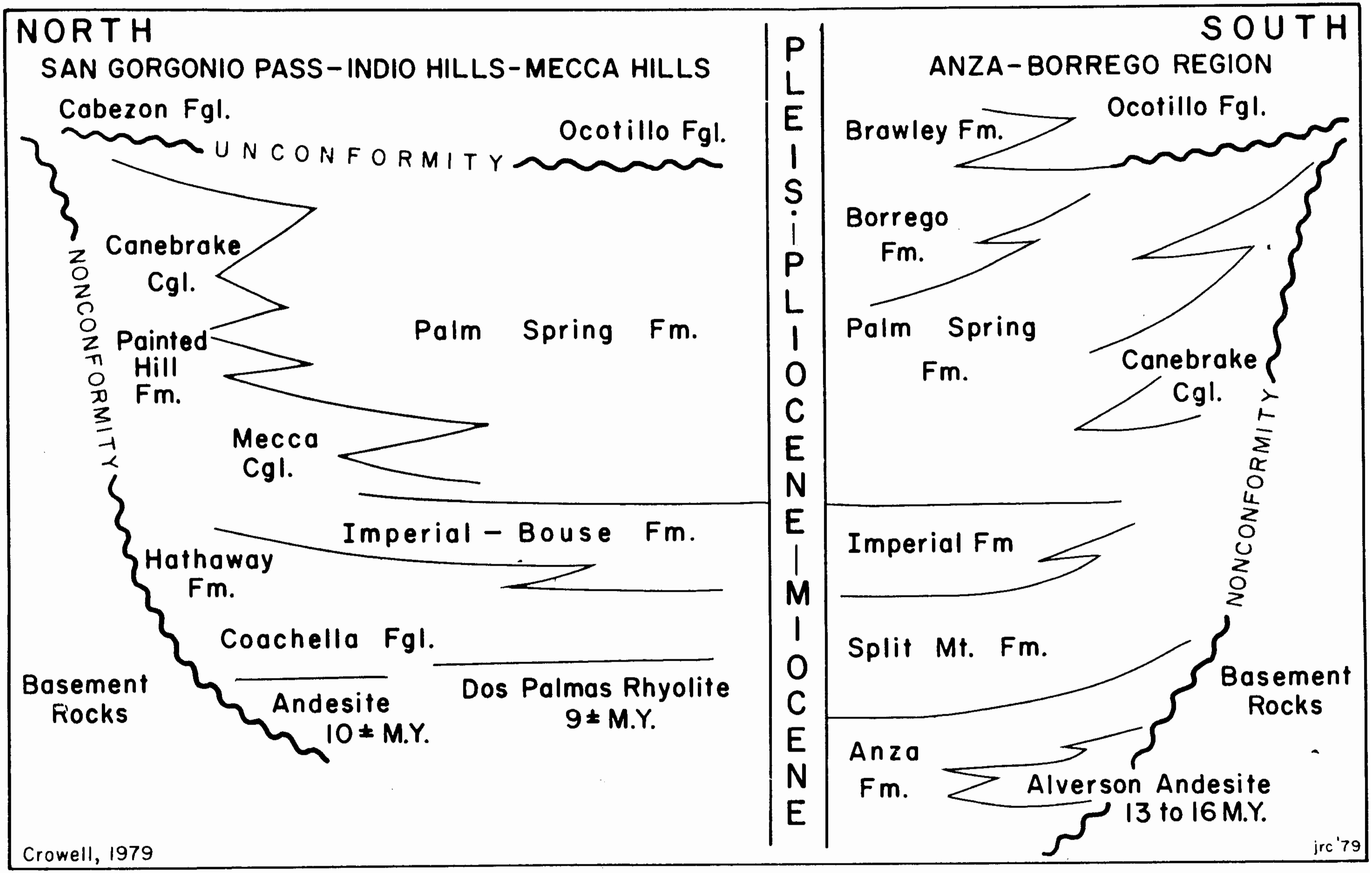


Fig. 4. Stratigraphic diagrams for late Cenozoic strata in Salton Trough for northern and southern parts of the basin (From Crowell and Baca, 1979).

intrusions. The Orocopia Mountains represent a tectonic window through North America plate to the top the ancient, subducted Farallon plate that became exposed when part of the North American plate slid off by detachment faulting in Miocene time. The mountain mass consists almost entirely of gray and green schist virtually identical in composition and origin to divers large schist bodies elsewhere in southern California, particularly its offset equivalent, the Pelona Schist in the San Gabriel Mountains.

The mountains southwest of the Salton Trough represent part of the great southern California batholith that stretches uninterruptedly from Los Angeles southward to La Paz in Baja California. Jurassic plutonic rocks range from gabbro to granite, but the average rock is tonalite, whereas that in the Sierra Nevada is granodiorite and quartz monzonite. The country rocks for the southern California batholith are Paleozoic miogeoclinal sedimentary rocks of the Winchester Series, now contact metamorphosed to argillite, mica schist, marble, and quartzite. Much of the mountain mass west of the Salton Sea was strongly mylonitized during Miocene detachment faulting and extension.

Faults and Active Tectonics

The rift and transform system of Gulf of California extends beneath the thick sedimentary cover of Imperial Valley where it spawned local rhyolitic volcanism, formation of stepover basins, and a system of strike slip faults whose frequent earthquakes make the region the most seismically active in California (Fig. 5). The main strike-slip faults, San Andreas and San Jacinto, bound the Salton Trough as a right-shear couple, between which left-slip cross faults bound a series of thin crustal slabs that rotate clockwise in the shear couple (Figs. 6A and B). These slabs rotate upon subducted Farallon plate, now captured by and moving northwestward as part of the Pacific plate. In at least one instance, the 1987 Superstition Hill earthquake, an M6.2 earthquake on one of the cross faults triggered a M6.6 earthquake 11 hours later on the San Jacinto fault system (Fig. 7).

There can be no doubt of the high level of late Pleistocene and Holocene activity of the faults in Salton Trough judging from abundant physiographic and geomorphic features, including faulted landslide deposits, faulted alluvial fans and terraces, truncated spurs, deflected drainages, sags, scarps, shutter ridges, aligned

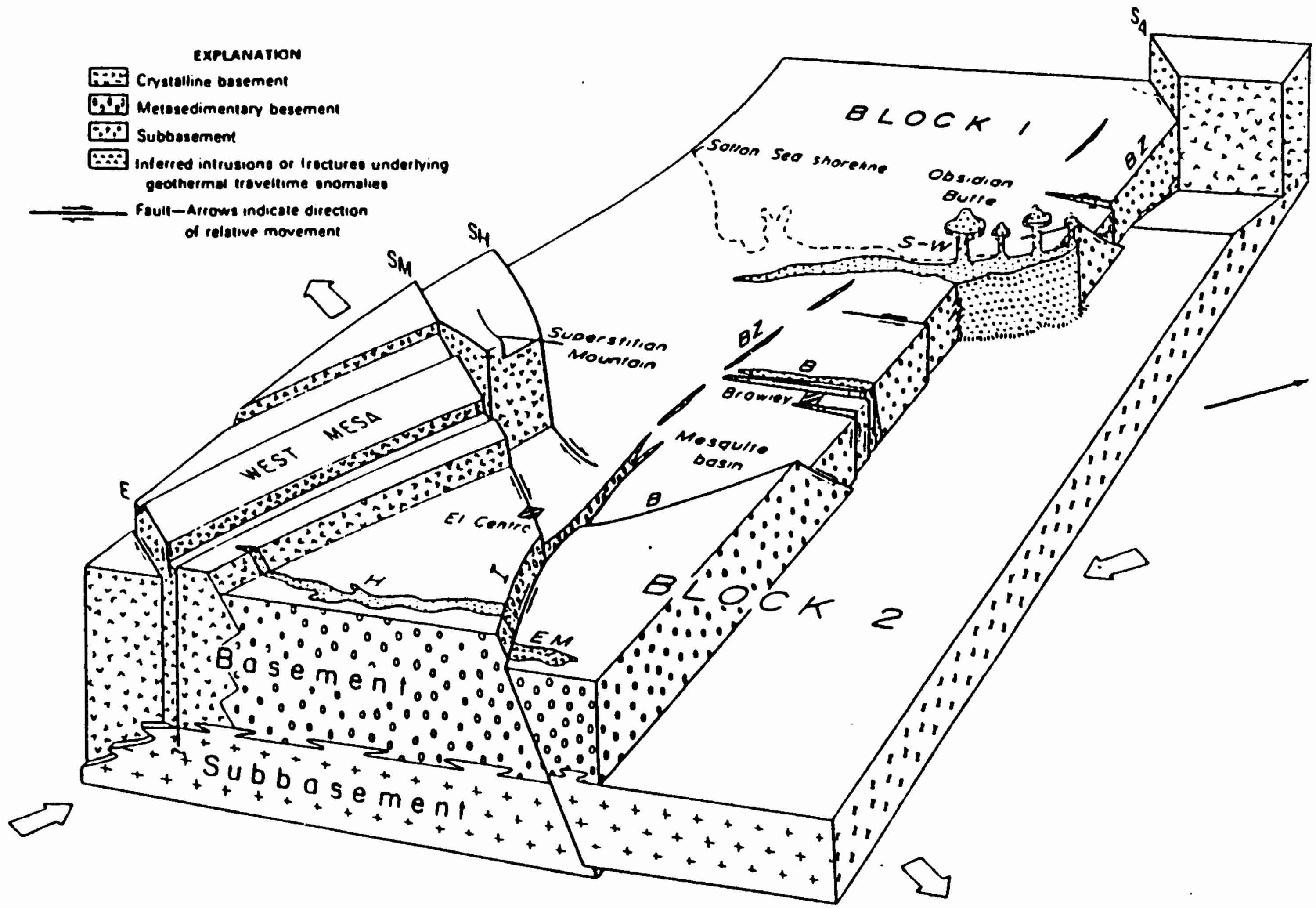
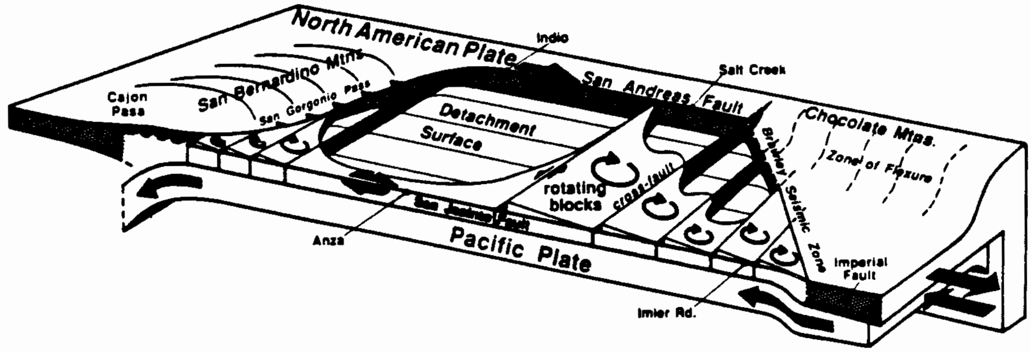


Fig. 5. Schematic block diagram of Imperial Valley region, with sedimentary rocks removed and basement cut away along a line roughly parallel to Brawley seismic zone. Geographic names are projected downward onto basement for reference. Abbreviations: B, Brawley fault zone; BZ, Brawley seismic zone; E, Elsinore fault; I, Imperial fault; SA, San Andreas fault; SH, Superstition Hills fault; SM, Superstition Mountain fault. Geothermal areas: B, Brawley; EM, East Mesa; H, Heber; S, Salton Sea; W, Westmorland. Shaded arrows indicate dominant extension and contraction directions for recent geologic past. Blocks 1 and 2 move away from Brawley seismic zone - and from inferred spreading center - in direction parallel to southern section of Imperial fault. Stepover basins form at Mesquite basin and Salton Sink which is presently occupied by Salton Sea. (From Fuis et al 1982; Fuis and Kohler, 1984).

A.



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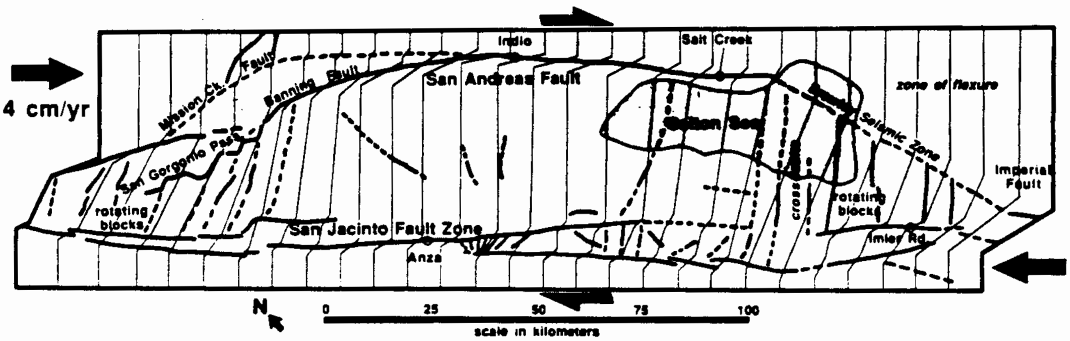


Fig. 6A. Hypothetical model of major detachment beneath Salton Trough from Brawley seismic zone to San Gorgonio Pass. Deformation in upper plate is partly the result of traction across this detachment. Slip on the detachment causes lithospheric thinning at the Brawley seismic zone, and thickening at San Gorgonio Pass. Higher long-term slip rates at Indio than at Salt Creek on San Andreas fault, and at Anza than at Imler Road on the San Jacinto fault, are explained by redistribution of displacement into block rotation and slip across the width of the zone from the San Jacinto to the San Andreas. (From Hudnut et al, 1989).

Fig. 6B. Strain distribution across the San Andreas and San Jacinto fault zones, consistent with the hypothetical model (6A). Displacement lines are rotated across areas where crustal blocks, bounded by left-lateral cross faults, are rotated due to right lateral plate boundary shear across the entire zone, in particular near San Gorgonio Pass and the Brawley seismic zone. Strain is partitioned into translational and rotational components. (From Hudnut et al., 1989).

valleys, and linear ground water barriers. Paleoseismologic investigations have given some insights about the pre-historic activity of some of the faults.

The largest historic shaker was the 1940 El Centro earthquake (M7.1) on the Imperial fault. That earthquake displaced the U.S. - Mexico boundary 5.8 m right laterally. A M6.6 earthquake occurred on the same fault in 1979, but all of the displacement was on the U.S. side of the border, and maximum right lateral displacement was only 1.5 m. Other notable right-slip earthquakes have occurred on the Mission Creek fault (1948, M6.4), southern San Jacinto fault (1968, M6.8), the Banning fault (1986, M6.2), and the Superstition Hills fault (1987, M6.6).

The fault segment from San Gorgonio Pass to Durmid Hill (Fig. 3) is one of the most seismically inactive stretches of the San Andreas fault along its entire 1000 km length. Significantly, no major earthquakes have been recorded along that segment in the last 350 years by historic or paleoseismic studies, although the geomorphic evidence is clear that the fault has been very active in Holocene time. With so much historic activity at each end of this segment of the fault, as well as along much its remaining length in California, however, seismologists are understandably concerned that the probability of a major earthquake here is quite high - perhaps as high as 50 percent in the next 30 years.

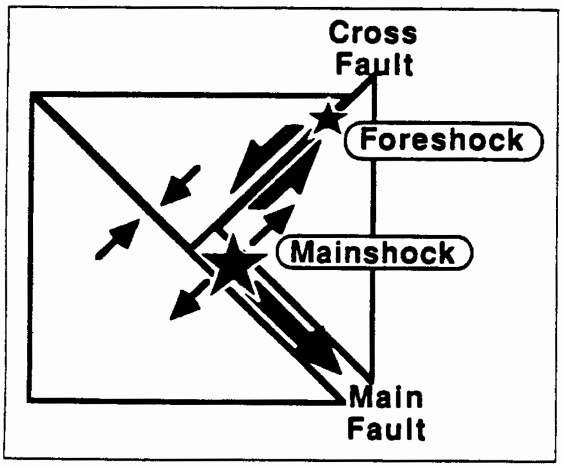


Fig. 7. Diagram of cross-fault triggering mechanism. Rupture of cross fault compresses and decompresses adjacent segments of main fault, strengthening and weakening the fault. After a delay, rupture starts on main fault in area of decompression. Rupture then propagates away from the intersection. This model works for the November 1987 Superstition Hills earthquake sequence and (by mirror symmetry) predicts that future rupture on cross faults farther northwest may trigger a great earthquake on the southern San Andreas fault. (From Hudnut et al., 1989).

GEOGRAPHY, PHYSIOGRAPHY, AND RECENT HISTORY OF THE SALTON SEA

(After R. M. Norris, 1979)

The Salton Sea, the largest lake in California, is a man-made feature whose origin is not entirely unrelated to its various predecessors collectively known as Lake Cahuilla (named for a group of intrepid Indians who inhabited the region). It is much smaller than Lake Cahuilla, of course, with a length today of about 55 km, a width of 22 km, a depth of about 15 meters, and an area of 910 km^2. Its present surface lies about 71 meters below sea level and is rising a few centimeters per year.

The lake occupies a small part of a very large structural trough extending from the foot of San Gorgonio Pass on the north, southeastward for about 1000 miles into Mexico. The Gulf of California between Sonora and Baja California in Mexico occupies most of this depression. The extreme northern end of the depression, from the foot of San Gorgonio Pass to the northern limit of the Salton Sea, is usually called the Coachella Valley. About half of this valley lies above sea level and about half below sea level. The zero contour follows the foot of the Santa Rosa Mountains west of the Salton Sea and crosses the floor of the valley near Indio and then skirts the foot of the Mecca Hills and Orocopia Mountains on the east side of the Salton Sea.

Southward from the Salton Sea to the Mexican boundary, the depression is usually known as the Imperial Valley, a term invented about 1900 by a group of real estate promoters who wanted a more attractive name than "Salton Sink" so that they might entice settlers to the area and make money. Their choice of names stuck and they did entice settlers to the area. They didn't do so well with respect to the money, however.

From the Mexican border to the head of the Gulf of California, the depression, mostly above sea level, is usually called the Colorado Delta. Actually, of course, the delta extends northward to include much of what is called the Imperial Valley.

Lake Cahuilla had disappeared by 1700 because travelers after that date did not report any lake in the valley. The present Salton Sea came into being early in the 20th century as a consequence of the settlement and agricultural development of the fertile farmlands in the Salton Trough beginning in the 1890s.

While settlers were enticed into the valley by real estate and farm promotions at the end of the 19th century, a company was formed in 1896 to bring irrigation water to the Imperial Valley from the Colorado by means of canals. Work began on the canal system in 1900. By then about a thousand settlers were in the valley and some 650 kilometers of canals were in service by 1902. Additional hordes of settlers arrived in the years 1903 and 1904 and taxed the water system to such an extent that the head gates at the Colorado were removed to permit more water to enter the silted channel of the Alamo River during low water stages. At the end of 1904, more than 40,000 ha of agricultural land were under irrigation.

Owing to the presence of the large Algodones sand dune chain extending into Mexico, it was necessary to place the river intake works on the west bank of the Colorado River in Mexican territory. Water was conducted from the intake through Mexican canals to the international border where it passed into the American canal system. This, of course, involved setting up a Mexican corporation to collect and deliver the water to an American company, which then delivered it to the settlers in the valley.

In those days, of course, the Colorado River was completely undammed and subject to extreme fluctuations in volume. By the end of 1904, the river was at a very low stage and the canals were badly choked with silt. The settlers were clamoring for more water and the irrigation company applied to the Mexican government for permission to install new headgates. Long delays occurred and the company, in the interim, by-passed the existing headgates and built wing dams in the river to draw more water out of the low river. Unfortunately, in January 1905, a major flood occurred in the Colorado River, followed by three flash floods in February. A great deal of water began to enter the canal system through the open by-pass. Engineers for the water company hoped to close the gap in late spring during the normal low water period, but it was not to be; that year there was no low water period. The water remained high in the river through the spring and into the summer.

Early in the summer of 1905, about 16 percent of the Colorado's flow was estimated to be entering the canal system, and by October that same year, virtually the entire river flowed into the Salton Trough. A new lake formed rapidly in the floor of the basin; the New Liverpool salt works and the Southern Pacific railway line were flooded. Deep channels, now known as the New and Alamo Rivers, were quickly cut into the soft valley sediments. An ironic result of all this was that the canal system largely dried up because the channels carrying the river water had cut well below the canal level at many places.

The river remained at an abnormally high level all spring and summer and the company, in hot water with the New Liverpool Salt Company and alarmed settlers who saw the entire volume of the Colorado pouring into the valley, gave up efforts to control the river until low water in the fall.

The financial resources of the irrigation company were exhausted by its efforts to control the river, and so in desperation it turned over control to the Southern Pacific Railway Company, who took charge and managed to close the break late in 1905. A few weeks later, yet another flash flood came down the river and took out the dikes just completed. The new control gates were completed in early 1906, but the river was not contained until November that year. In early December, yet another flash flood came down the river, this time from the Gila River, a tributary that enters the Colorado near Yuma, just a short distance above the break. Because the break was on Mexican territory, the federal government was unable to act and President Theodore Roosevelt appealed to the Southern Pacific to make still another attempt to close the break. Final closure was effected in February 1907.

By that date, the Salton Sea was a lake appreciably larger than the present lake. Its surface stood at 60 m below sea level (now 71 m). The channels of the New and Alamo Rivers were gorges as much as 0.4 km wide and 15 m deep cut into the valley floor silt. Both rivers had demonstrated spectacular rates of headward erosion during the formation of the lake. Waterfalls 5 to 10 m high migrated up the New River to the Mexican border, a distance of about 80 km in two years. In the Alamo River, headward erosion of the same sort, extended upstream 48 km in the same period.

The Salton Sea reached a maximum size in February 1907 with its surface at 198 feet below sea level. The lake subsequently shrank in size until about 1940 when waste irrigation water caused it to rise from a minimum of about 250 feet below sea level.

Salinity of the Salton Sea was at first rather low, despite the presence of salt flats on the valley bottom, but over the years as evaporation of the water has occurred, salinity has increased to the point where today it is about equal to that of the sea, although the distribution of salts is different. Sulfates, for example, are much higher in the Salton Sea than in the ocean. Salinity will continue to increase both because of the great evaporative loss of water and because much of the inflow consists of water which has been used to leach salts out of the agricultural soils in the valley.

Over the past thirty years or so there has been much discussion about the level at which the lake will eventually stabilize. Assuming that the present inflow, chiefly from waste irrigation water, remains the same, the increasing evaporative loss as the lake area increases should, theoretically, at some time in the future bring inflow and evaporative loss into balance. Most predictions suggest that the lake is near that level now. Average evaporative loss is about 2.5 to 3.0 meters per year, but because of variations in evaporation and inflow, the lake tends to reach an annual maximum level in April and a low level, about 25 cm below the high, in October. Needless to say, the gradual rise in lake level over past forty or fifty years has had an adverse effect both on recreational facilities along the lake shore and on agricultural activities. Appreciable amounts of land cultivated just a few decades ago have been abandoned due to flooding or to the build-up of salts in the soil as the lake level rose.

LAKE CAHUILLA HIGH SHORELINES

(after R. M. Norris, 1979)

A series of lakes, collectively as Lake Cahuilla, occupied the Salton basin during Quaternary time. The older of these have been dated at about 37,000 years BP, and the associated shorelines have been identified at levels ranging from about 40 to 49 m above sea level. The older shorelines seem to have been warped and now merge with the clearer Holocene shorelines in the northern part of the basin. It is the Holocene shorelines that stand out so clearly today. The Holocene shoreline also shows some evidence of warping, but it generally lies between 13 and 15 m above sea level. Holocene lakes seem to have repeatedly occupied the basin during the last several thousand years and the most recent, pre-Salton Sea filling is thought to have occurred about 1650 years ago, but may be as recent as 300 to 500 years old (Hubbs et al., 1963, 1965). A brief marine invasion may have occurred during the Pleistocene (Hubbs et al., 1963, 1965).

The passing of Lake Cahuilla has left many mementos of its existence scattered about. Many shoreline features formed by wave action around Lake Cahuilla. Among these are shore cliffs as much as 10 m high, extensive beaches, recessional shorelines, bay mouth bars, spits, tombolos, and long barrier beaches where the lake bottom had a gentle slope. Extensive travertine coatings cover the rocks below the most obvious old shoreline which stood about ~0 feet above sea level; abundant delicate shells of mollusks inhabiting the lake are found; old beaches, bars, spits and shoreline features are clearly preserved. On the western side of the Salton Basin, particularly along the base of the Santa Rosa Mountains in the vicinity of Travertine near the Imperial County line, the shoreline is marked by steep boulder beaches and commonly by thick deposits of calcareous tufa coating the rocks below the high water level. In this region, the old shoreline stands out, sharp and clear, on the mountainside, appearing much like a bathtub ring after the water has gurgled down the drain. George Stanley has recognized a fainter, higher shoreline at 160' above sea level.

W. P. Blake, a young geologist, attached to the Pacific Railroad Survey party, published a report in 1856 which was the first to suggest that the Coachella and

Imperial Valleys lay below sea level and that they were due to the evaporation of the part of the Gulf of California cut off by the construction of the Colorado River Delta.

The Colorado River and its delta regulate the alternating filling and evaporation of the lake. The delta is a large, crudely fan shaped structure extending across the Salton Trough; the river discharged alternately into the closed depression to the north and into the Gulf of California. It is not clear how many times the river filled the Salton Basin, but it has been suggested that the last great flooding that produced ancient Lake Cahuilla occurred at the end of the Pleistocene or early in the Recent epoch. Some authorities have expressed the opinion that Lake Cahuilla finally lost its last drop to evaporation about 400 years ago.

It now seems obvious that if such a sequence of events did occur, then it had to commence after early Pliocene time, because the last marine strata deposited in the basin belong to the Imperial Formation whose age is mostly Miocene, possibly including early Pliocene. Nearly all subsequent deposits are non-marine lake beds, fluvial, and fan deposits reaching thicknesses of more than 6000 m in some places. This great thickness, moreover, is proof that the basin is a subsiding one.

GEOLOGY OF THE MECCA HILLS

Arthur Gibbs Sylvester and Alula Damte

The Mecca Hills are a northwest/southeast-trending structural culmination along the San Andreas fault zone, as are the Indio Hills about 30 km to the northwest, and Durmid Hill about 12 km to the southeast (Fig. 3). They have been squeezed up along the fault in shortening deformation accompanying northwest-southeast horizontal shear (Sylvester, et al., 1993; Damte, 1996) - a general process termed "transpression" (Harland, 1971; Sylvester and Smith, 1976). The strike of the fault between the three hills is parallel to the plate motion vector, whereas it is from 5° to 7° counterclockwise of the plate motion vector adjacent to the hills (Bilham and Williams, 1985). Thus, the three hills are in the position of restraining bends, or restraining stepovers, in the fault, accounting for the transpressional deformation in each of the hills.

The San Andreas fault is located along the southwest side of the Mecca Hills where it is clearly marked on the surface by a nearly straight, 20-50 m-wide zone of red brown gouge and crushed rock. The fault may dip about 75° NE judging by the distribution of small earthquakes about 1 km northeast of its surface trace. The fault's gravity signature is large (6 mg/km) and impressive (Fig. 8), one of the steepest in California, in fact, indicating a basement step of about 4000 m from the surface exposure in the core of the hills to a position beneath the town of Mecca.

The rocks and structure of the Mecca Hills have been described and discussed and summarized by Sylvester and others in several publications (e.g., Sylvester and Smith, 1976; Damte, 1996), one of the most recent of which follows this introduction. Several additional noteworthy aspects of the stratigraphy and structure lead to tectonic inferences that merit cursory presentation here.

1) Stratigraphic Aspects - The rocks in the Mecca Hills consist of late Neogene lacustrine, fluvial, and alluvial fan deposits of the Mecca and Palm Spring formations deposited on a peneplained surface of both Late Proterozoic migmatite gneiss and Mesozoic Orocopia Schist (Fig. 4). We now believe that they accumulated in a little sub-basin - the Mecca Hills basin (Damte and Biehler, 1995; Damte, 1996) between the San Andreas and Painted Canyon faults (Fig. 9), based

on palinspastic considerations of fault slip, on the arrangement of strata in the basin, on gravity data, and on a suite of unique metamorphic clasts in the Plio-Pleistocene Palm Spring Formation (Damte, 1996).

Most of the Palm Spring Formation consists of alternating lacustrine and fluvial arkosic sandstone and siltstone beds with conglomerate lenses from a granitic provenance northeast of the San Andreas fault. Some of the fine-grained sediment may have come down the Colorado River drainage to the basin. Today the strata constitute a thick succession of beds, which, although strongly folded locally, are arranged in a shingled, northwest dipping sequence. The depositional arrangement of the beds, especially between Box and Painted canyons, is similar to that exposed in strike-slip basins elsewhere, notably Ridge and Little Sulphur Creek basins in southern California, and Kvamshesten and Hornelen basins in Norway (e.g., Nilsen and McLaughlin, 1985). Paleocurrent indicators support the hypothesis of northwest to southeast sediment transport down the axis of a narrow, elongate basin between two subparallel faults, one of which is now the San Andreas fault.

A distinctive suite of marble, biotite schist, quartzite, and mylonitic gneiss clasts is present in a conglomeratic horizon between the lower and upper members of the Palm Spring Formation (Dougherty, 1994). The distribution of the clasts close to and along the San Andreas fault, and the way that they diminish in size and quantity southeastward, imply that their source was on the southwest side of the basin, probably southwest of the San Andreas fault. In fact, remarkably similar rocks crop out in the Palm Desert area of the Santa Rosa Mountains, approximately 35 km to the northwest, on the Pacific plate side of the San Andreas fault. We considered other sources for this rock suite, yet none has the same type of marble, and none is east of the San Andreas fault. Although the age control for the Palm Spring Formation is weak, the displacement of the distinctive clasts from their source yields a permissive slip rate for the Mecca Hills segment of the San Andreas fault of 17 - 35 mm per year in the last 1.8 Ma (Dougherty, 1994).

2) Structural Aspects - The central Mecca Hills are cut by three major faults (cover illustration, Sylvester 1992): The San Andreas, the Skeleton Canyon, and the Painted Canyon faults. We believe that the Painted Canyon fault was a normal fault during early stages of its history, and only after deposition of much of the Palm Spring Formation and during subsequent inversion of the Mecca Hills basin

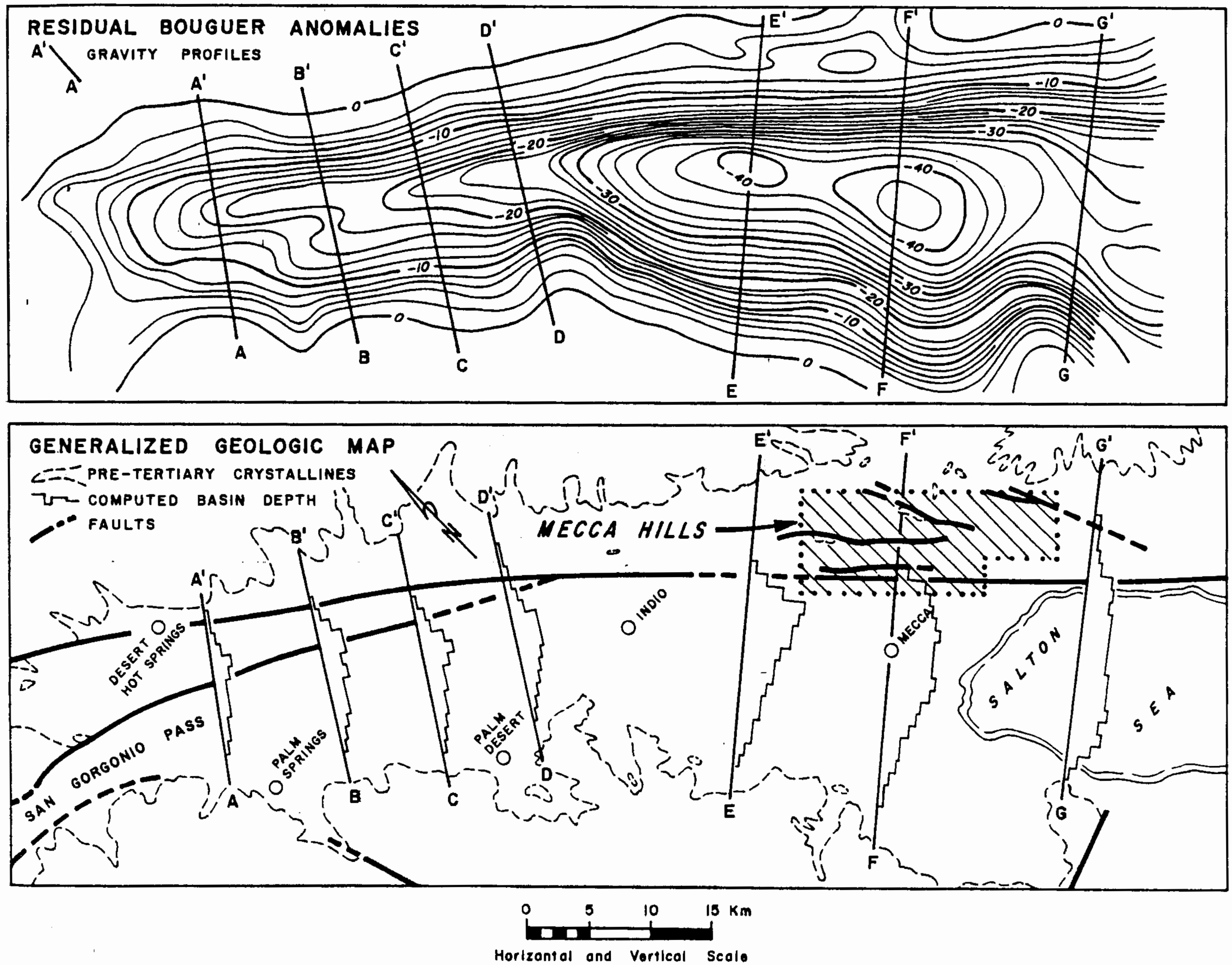


Fig. 8. Residual Bouguer anomalies and computed basin depth profiles across Coachella Valley. (From Biehler et al., 1964).

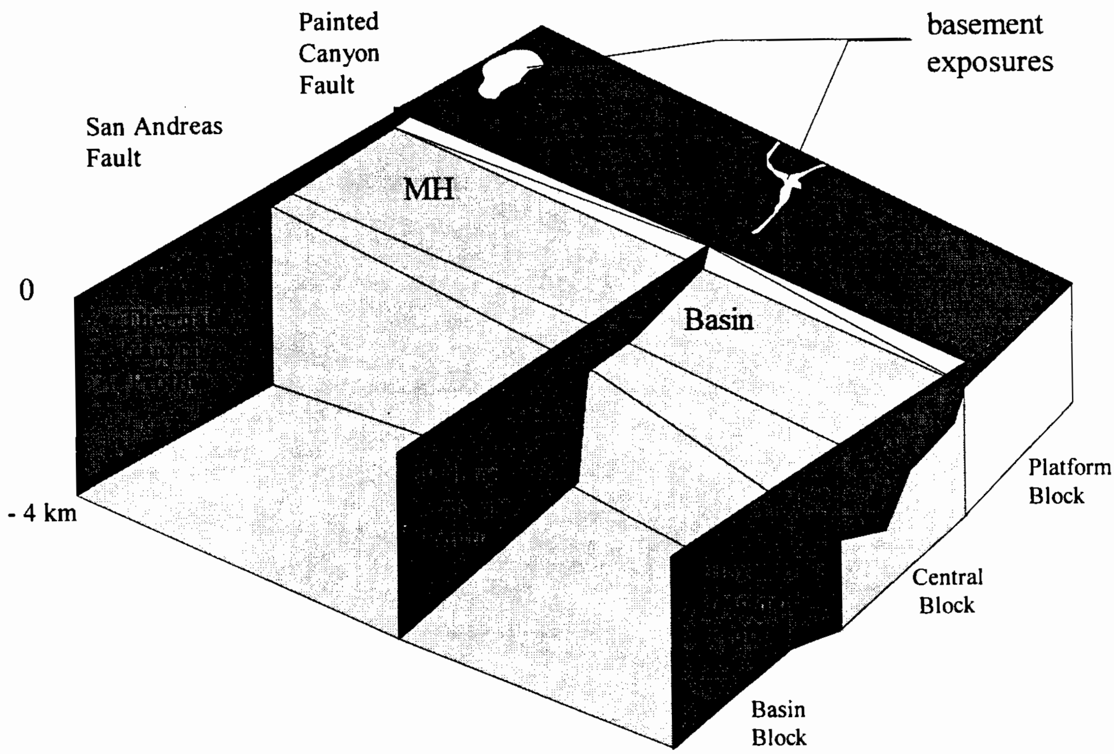


Fig. 9. Schematic block diagram of the subsurface structure of the Mecca Hills, including Mecca Hills basin, the Painted Canyon and San Andreas faults (From Damte, 1996).

did it begin to act as a right-lateral reverse-slip fault. As a corollary, we recognize that the Mecca Formation in Painted Canyon was deposited in buttress unconformity against the surface of the normal fault, but we agree with Sylvester and Smith (1976) that the depositional surface was not a surface of slip during cataclastic shear and subsequent folding of that surface and of the overlying Mecca Formation.

3) We suspect that one of the main elements of the Sylvester and Smith (1976) "palm tree structure" - the Skeleton Canyon fault - may be an out-of-the-syncline fault rather than a strike-slip fault parallel to, and acting in concert with, the San Andreas fault (cover illustration, Sylvester, 1992). Sylvester based that conclusion on much detailed field mapping that he and his students did in the 1990s, and upon Rymer's (1991) finding that the northwest end of the fault terminates in an anticline whose axial surface is parallel to the fault.

The Skeleton Canyon fault dips northeastward from 35° to 70° between Box and Thermal Canyons (Fig. 10). Deep in the canyons it crosses, its dip is steeper than on adjacent ridges, so that the fault has a convex-upward profile in cross section. Locally it carries sandstone of the southwest limb of Skeleton Canyon syncline short distances upward and outward over a sequence of brown sandstone and siltstone that we regard as distal equivalents of proximal Mecca Formation breccia and alluvial fan deposits now exposed in Painted Canyon. En echelon folds, so commonly regarded as characteristic of strike-slip fault zones, are limited to a zone less that 300 m wide on each side of the San Andreas fault, less than 50 m wide adjacent to the Skeleton Canyon fault near Box Canyon, and less than 100 m wide southwest of the Painted Canyon fault. All orientations of slickensides may be found on the surface of the Painted Canyon fault, from down dip to horizontal, but the down dip set predominates. We infer that the fault cuts down section and flattens at depth in the limb of the Skeleton Canyon syncline in the way that mesoscopic out-of-the-syncline faults do on both limbs of the syncline. Excellent examples of such faults are clearly exposed near the contact of the Palm Spring and Mecca formations on the northeast limb of the syncline in Painted Canyon (Sylvester and Smith, 1976).

Detailed gravity profiles across the Mecca Hills in Box, Painted, and Thermal canyons define a 30 mgal anomaly across the San Andreas fault,

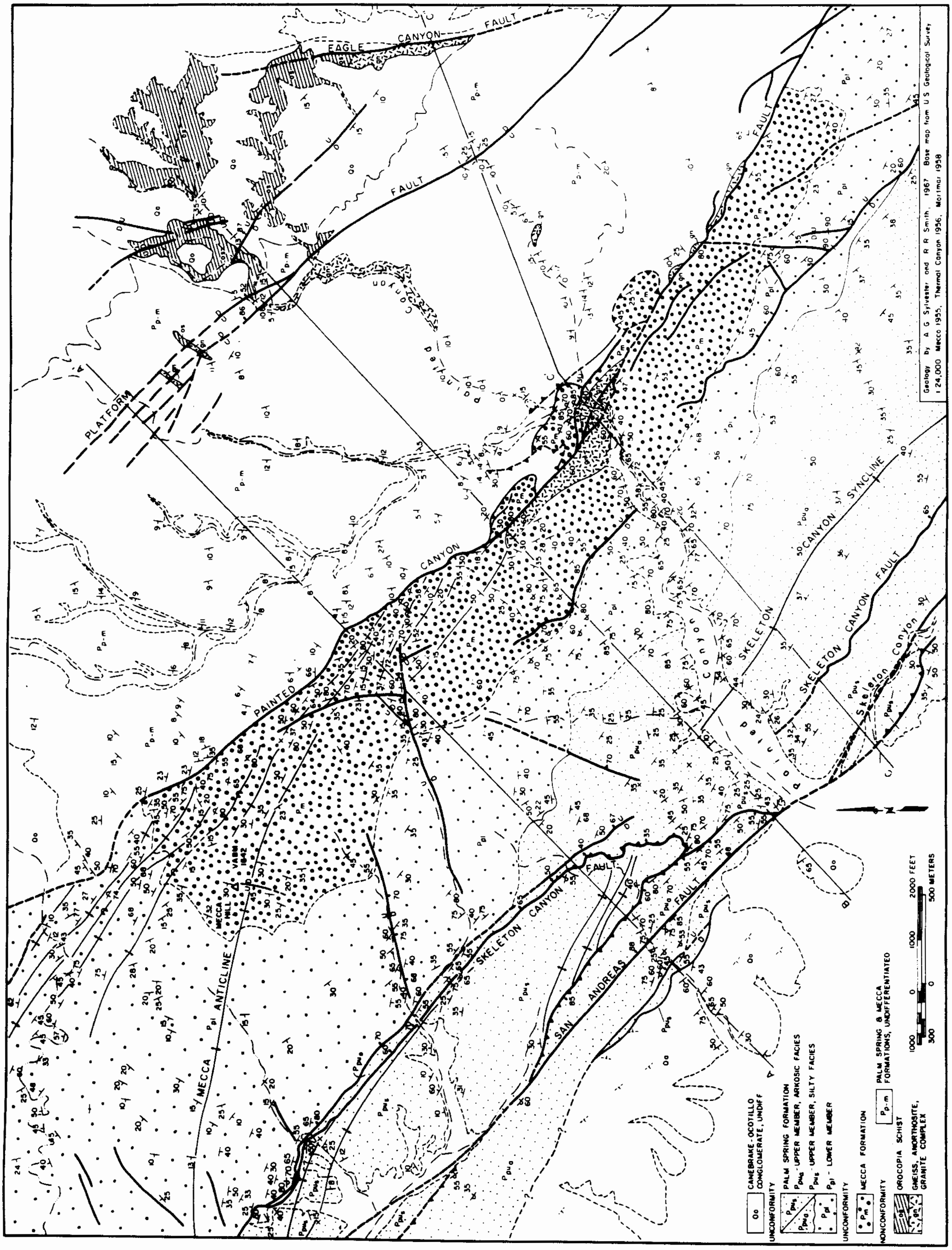
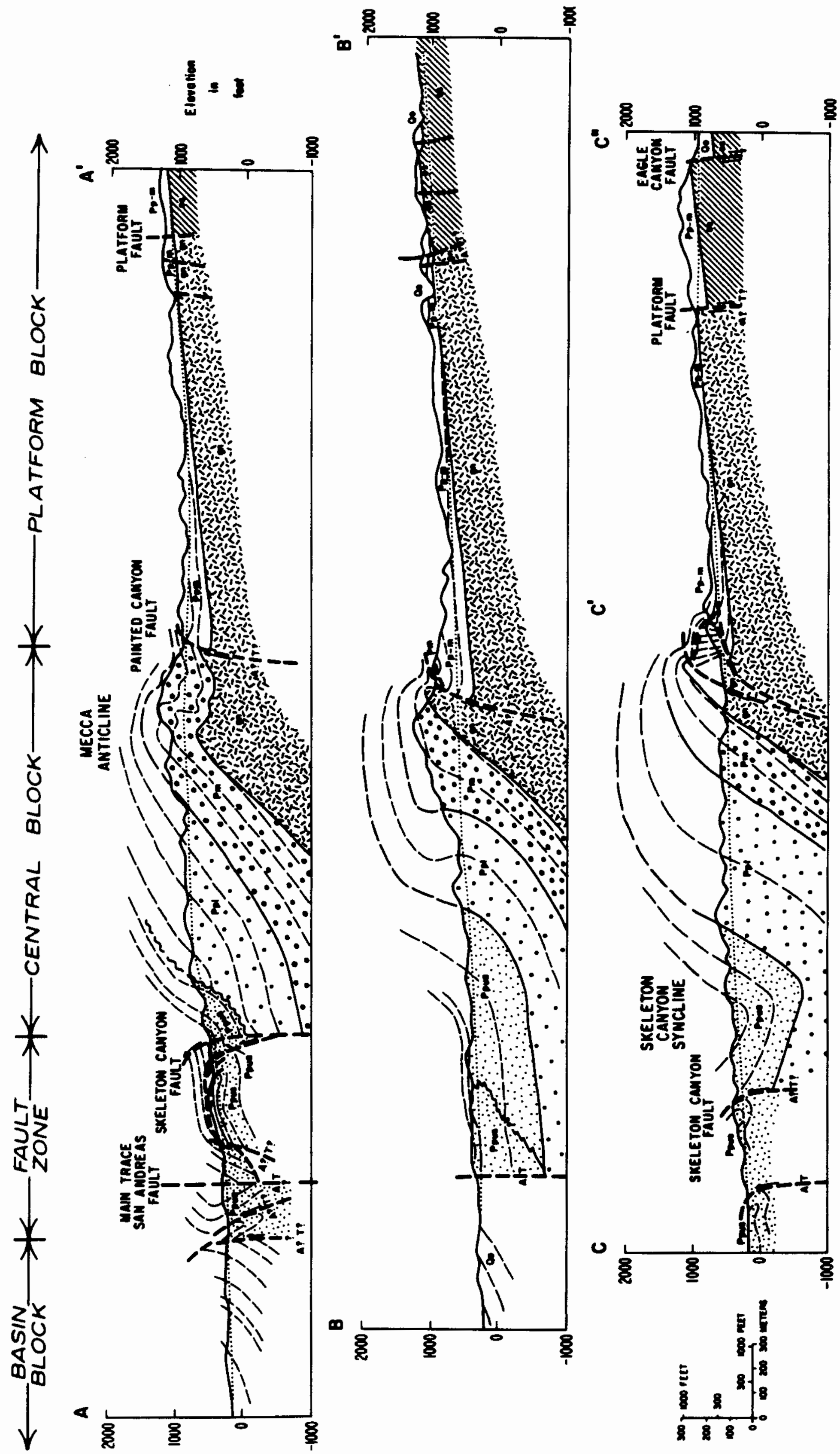
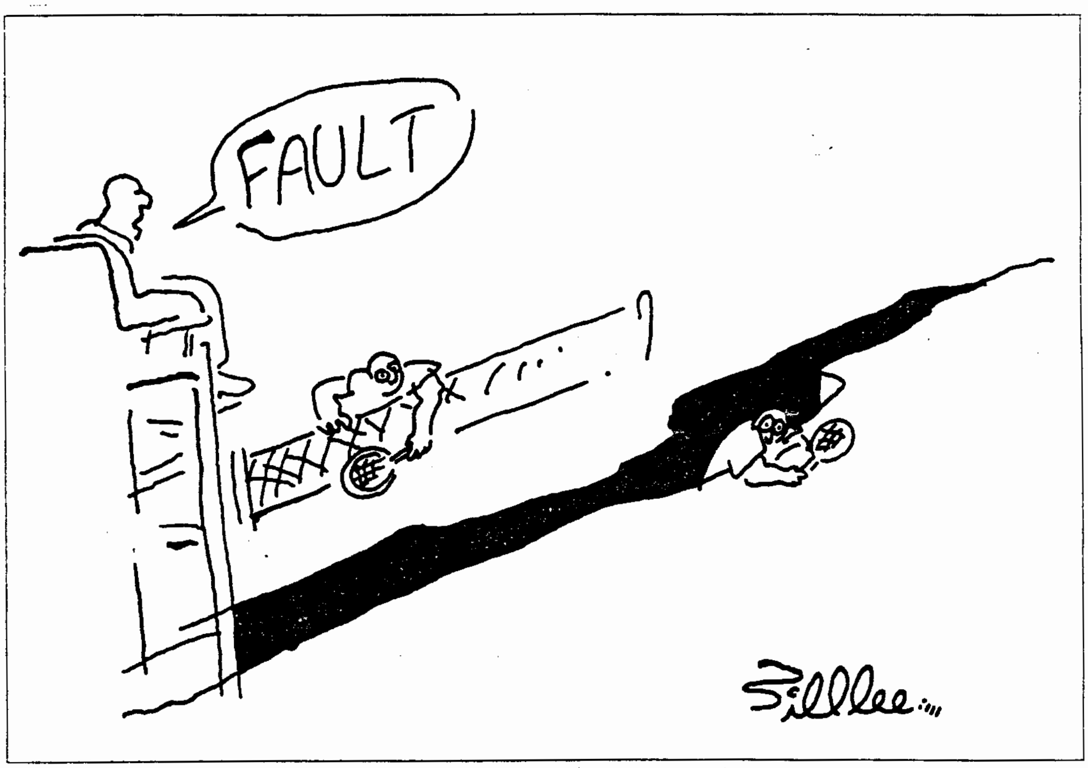


Fig. 10. Geologic map and three cross sections of the central Mecca Hills (from Sylvester and Smith, 1976)


BASIN BLOCK
FAULT ZONE
CENTRAL BLOCK
PLATFORM BLOCK
A
A'
MAIN TRACE SAN ANDREAS FAULT
SKELETON CANYON FAULT
MECCA ANTICLINE
PAINTED CANYON FAULT
PLATFORM FAULT
Elevation in feet
2000
1000
0
-1000
B
B'
C
C'
C"
SKELETON CANYON SYNCLINE
SKELETON CANYON FAULT
PLATFORM FAULT
EAGLE CANYON FAULT
1000 FEET
300 METERS

equivalent to 2500 m vertical separation of the basement surface (Damte and Biehler, 1995; Damte, 1996). We infer that much of that vertical separation across the fault occurred during strike-slip after the Palm Spring Formation was deposited.

Tectonic Inferences - The principal conclusion that we draw from these observations is that transpression in the Mecca Hills is partitioned among several structures, as follows (cover illustration): as strike-slip along the San Andreas fault; as reverse-right slip along the Painted Canyon fault which, before transpression, was a normal fault during late Miocene extension; and as shortening of strata between the two faults, expressed as folding and out-of-the-syncline thrusting. Strike-slip on the San Andreas fault is a minimum of 35 km since deposition of the base of the upper member of the Palm Spring Formation which itself is less than 1.8 million years old (Boley et al., 1994) To the extent that basement rocks in the Mecca Hills correlate strongly with similar rocks in the San Gabriel Mountains (Crowell, 1962), 300 km to the northwest, the post-Pliocene slip of the Mecca Hills is probably much more than 35 km. ----- and is it still continuing!



Road Log

Drive northwest about 9 miles on State Hwy 111 from Mecca Beach State Park campground to State Hwy 195 at Mecca (Fig. 11). Turn right and follow Hwy 195 northeast up Box Canyon and obliquely across the Mecca Hills about 15 miles to wide area in road.

PAUSE STOP. We stop here briefly to stretch and to view northward across Box Canyon Wash and I-10 in the middle distance to the Little San Bernardino and Cottonwood Mountains on the skyline in Joshua Tree National Park. The mountains about 5 km to the east are the Orocopia Mountains. All of the area in sight drains down Box Canyon Wash and is the reason why flash floods are so frequent, large, and destructive in the canyon.

The mountains we see in Joshua Tree NP consist of the dark brown gneiss of Proterozoic age (part of the Chuckawalla Complex of Miller, 1944), intruded by Proterozoic and Mesozoic granite (light gray rocks). These rocks underlie the thin cover of alluvium between the mountains and us and, together with the Orocopia Schist, form isolated basement exposures in the Mecca Hills. The bulk of the fluvial and alluvial strata in the Mecca Hills was derived from the mountains in our view.

The Orocopia Mountains consist primarily of Orocopia Schist as seen from our viewpoint. Along the north edge of the mountains a strip of rugged, dark brown Pinto Gneiss is separated from the smoother, gray schist by the Orocopia thrust. Some geologists speculate that the thrust, part of the regionally significant Vincent-Orocopia-Chocolate Mountains thrust, is nearly vertical here and acts as a strike-slip fault at the present time.

Retrace route down-canyon about 2-3 miles to Shaver Well which is marked by a large tamarisk tree and dark bedrock outcrops of schist.

0.0 STOP. **Shaver's Well** - set odometer to zero if desired

The purpose of this stop is to inspect the Orocopia Schist, one of the principal basement rocks on the northeast side of the Salton Trough and beneath the Mecca Hills. Here the schist is overlain nonconformably, or is in fault contact with, Pleistocene fanglomerate that dips gently down-canyon.

The Orocopia Schist at Shaver's Well is a greenschist facies albite-chlorite mica schist with an abundance of minor folds. This rock unit, probably ensimatic in origin, is confined to the footwall of the great Vincent-Orocopia-Chocolate Mountains thrust system of probably latest Mesozoic age. The volcanic rocks, greywacke, and mudstone that have since been metamorphosed may have been deposited in an ancient back-arc basin associated with Mesozoic subduction, or within an elongate rhombochasm associated with movements between the Kula and North American lithospheric plates. The thrust sheet has been folded in Mid-Tertiary time and later disrupted and dismembered from the Transverse Ranges region by Late Cenozoic right-slip along the San Andreas fault system.

Continue down-canyon on Hwy 195 toward Mecca

Pause Stops En Route in Box Canyon Wash

1.0 Another mile or so down-canyon, the white sandstone interbedded with pink fanglomerate about 100 m from the left side of the road is a stream delta consisting of resorted volcanic ash deposited in an interfan lake or pond area.

The Hidden Spring fault, kin of the Painted Canyon and Eagle Canyon faults, crosses Box Canyon Wash a mile or so down-canyon from the exposures of Orocopia Schist. Its location is marked by a large surface of nearly horizontal slickensides in calcite on fanglomerate. This is a very photogenic feature in the afternoon when the sun is on it.

And another mile or so down-canyon is a magnificent exposure of disharmonic folds in siltstone between thick, unfolded sandstone beds. Their origin is related to rapid sediment loading in a lacustrine setting, dewatering, and probable tectonic shaking. About 50 m down-canyon from the folds, the layering in the thick sandstone beds displays top-set, fore-set, and bottom-set beds of a Gilbert delta. The 5 m thickness of the succession represents the water depth at the time of deposition.

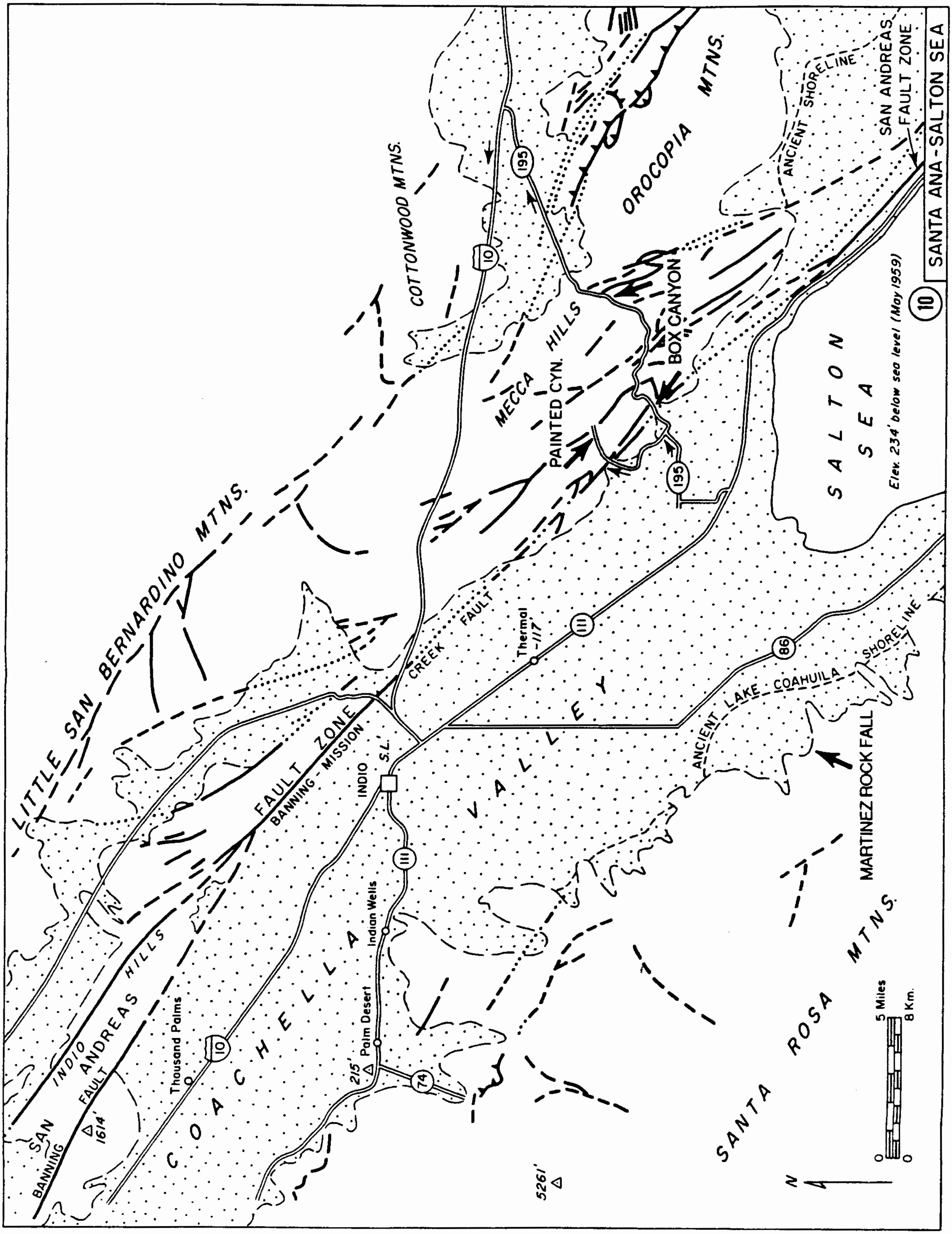


Fig. 11. Route and index map for Coachella Valley and Mecca Hills, Salton Trough.

3.0 In the upper half of Box Canyon Wash the fanglomeratic, fluvial, and lacustrine strata dip gently down-canyon toward the Salton Sea. About half way between Shaver Well and Coachella Valley, however, the road bends northwestward and proceeds from the gently dipping beds, across the Painted Canyon fault, and into a succession of steeply-dipping and folded strata assigned to the Palm Spring Formation. We shall not stop, except possibly for a photo op or two, because we'll see the same strata in Painted Canyon where the traverse is perpendicular to structure rather than oblique as it is here in Box Canyon Wash. As we drive down the canyon, we follow the axial trace of an anticline that is cut obliquely by faults, both dip-slip and strike-slip.

5.0 At the 30 mph left curve and in the canyon wall on the right (north) side, about 5 miles down-canyon from Shaver Well, is a gentle angular unconformity that separates the upper and lower members of the Palm Spring Formation. The unconformity may be mapped over a large area in the central Mecca Hills. In some places the beds above and below the unconformity are parallel, or nearly so as they are here; elsewhere they are perpendicular to one another.

7.0 Another mile or so down-canyon is the mouth of Box Canyon Wash. Here we cross the trace of the San Andreas fault and return to the Pacific plate at or very near a BLM information kiosk. The fault is poorly exposed on the right (north) side of the road where low outcrops of poorly resistant brown sandstone and siltstone are in a nebulous contact with fanglomerate that dips gently down-canyon. About 100 m down-canyon from the fault and on the right (north) side of the road is a cliff in uplifted and faulted Ocotillo Formation fluvial gravel and sand. The faults have both normal and vertical separations. Detailed inspection of the thickness variations of beds across faults indicate that the faults must have a component of strike-slip, which is not surprising given how close they are to the San Andreas fault.

If the air is clear, a good deal of the Salton Sea is visible to the south, and across the Coachella Valley are the Santa Rosa Mountains.

7.5 Intersection of Box Canyon road with dirt road to Painted Canyon.

Turn right on to Painted Canyon Road (Fig. 11). The road, a Riverside County easement across the Torres Martinez Indian Reservation, is generally suitable for standard automobiles, but beware of soft sand upon entering the main canyon all the way to the dead end turnaround. The road may not be passable after rainstorms due to flash floods and slippery mud.

En Route on Painted Canyon Road

The road proceeds northwest for 2 miles along the southwest margin of the Mecca Hills, parallel to a power line and to the San Andreas fault. The trace of the fault in the hills is marked by a 10-50 m-wide band of red-brown gouge separating distinctive Palm Spring Formation in the sandy, high badlands on the skyline from the smoother-weathering, low hills of Ocotillo fanglomerate in the foreground.

10.5 The road makes a broad right turn toward the mouth of Painted Canyon and crosses the San Andreas fault at a point 3 miles from the road intersection with Box Canyon Wash. The fault zone here is about 50 m wide and is marked on the right (southeast) side of the road by smooth, red-brown hills and knobs of fault gouge containing blocks and phacoids of sandstone, rarely limestone and granite. Excellent exposures of the gouge are in Skeleton Canyon about 1 km east-northeast the Painted Canyon road.

The most recently active trace of the San Andreas fault cuts across the mouth of Painted Canyon and continues northwest along the base of the sharp, straight front of the hills and thence through the low saddle on the skyline. A low, 100 m-long ridge of alluvium in the center of the canyon mouth is an erosional remnant of an older canyon floor. The canyon floor was uplifted and then eroded along its margins. That the ridge uplift involved more than one episode is evinced by the presence of one or two "terraces" on the sides of the alluvial remnant.

The general structure traversed by the road up Painted Canyon is that of an asymmetric antiform (Fig. 10), the Mecca anticline, with crushed basement rocks and a complex zone of faults, including the Painted Canyon fault, in its core. The structure is much more complex, however, because of strike-slip on the core faults. From the mouth of the canyon until we reach the basement, the canyon walls comprise lacustrine and fluvial strata of the Palm Spring and Mecca Formations. On the southwest limb of the Mecca anticline, the Palm Spring Formation is more than 1300 m (4200 ft) thick, whereas it is less than 100 m (300 ft) thick on the Platform block northeast of the Painted Canyon fault (Fig. 10).

11.0 Cross the axis of the Skeleton Canyon syncline about one-half mile up-canyon from the San Andreas fault and continue up Painted Canyon. Note the broad anticline on the left (northwest) side of the canyon, and see the closely spaced normal faults in the crest of the fold where it has been extended in flexural slip folding. The neutral fiber of the fold is almost at the floor of the canyon. The fold is one of several small folds in the trough of the large Skeleton Canyon syncline. They deform in flexural slip folding by crumpling of beds because of lack of space in the core of the syncline.

The Skeleton Canyon syncline, on the southwest flank of the Mecca antiform, is not well expressed in Painted Canyon, except for a few gentle reversals of dip, because the road crosses high in the structure where beds in the trough are nearly flat. About 300 m up-canyon, however, the beds steepen abruptly on the northeast flank of the syncline and dip consistently down-canyon (southwest) on the fold limb shared by the Skeleton Canyon syncline and the Mecca anticline.

Notice how the sedimentary strata coarsen as we proceed up-canyon. The generally thin-bedded, gently dipping, tawny, sandy and conglomeratic strata constitute the upper part of the Palm Spring Formation. Prominent greenish-siltstone interbeds characterize the lower member of the Palm Spring Formation about one-half mile from the mouth of the canyon. Bedding plane slip is concentrated along the siltstone beds in the strongly folded parts of the structure.

11.4 A few tens of meters before we enter the dark red-brown Mecca Formation, notice the little syncline and anticline in the Palm Spring Formation. Notice that the main folds, as well as small folds within the fold pair verge up-canyon, where the Mecca anticline and Skeleton Canyon syncline are upright or verge slightly southwest and west. Sylvester and Smith (1976) regarded these folds and their associated faults as products of out-of-the-syncline thrusting resulting from crowding of beds in the syncline in flexural slip folding. Close inspection of the canyon walls downstream from this locality reveals several other examples these faults.

11.5 En Route - The Mecca Formation and Basement Rocks

The Palm Spring Formation is underlain by the dark red-brown Mecca Formation, which comprises about 130 m of coarse breccia and conglomerate made of locally derived gneiss, schist, and granitic rocks. The contact between the Mecca and Palm Spring formations on the northwest canyon wall is a minor fault, but it is not perceptible on the southeast wall. About 300 m farther up-canyon from the Mecca-Palm Spring contact, varicolored outcrops of highly fractured and crushed basement rocks include black migmatite gneiss, white and pink granitic rocks, and light orange felsite dikes. The contact between the Mecca Formation and the basement is a buttress unconformity that is folded and faulted (Fig. 9). The Painted Canyon fault cuts through the central part of the basement outcrop on the northwest (left) side of the canyon, but on the southeast side, one of the main strands of the fault forms the contact between the basement and the Mecca Formation.

12.0 STOP End of maintained dirt road and public right of way. The tributary canyons must be traversed by foot.

Here the canyon branches into two main tributaries. The narrow, deep canyon on the right (northeast) offers a splendid transect into the platform block. The Plio-Pleistocene Mecca and Palm Spring formations at the mouth of the canyon are folded into a very gentle syncline. About 100 m up-canyon, the route proceeds down-section to the nonconformable contact of the strata upon Precambrian gneiss and granite (Fig. 12). The contact may be studied in detail when it is first encountered in the floor of the canyon, but it gradually rises higher on the canyon wall as the route proceeds up-canyon deeper into the basement. Mafic and granitic dikes intrude the gneiss. Notice how much less fractured and crushed the basement is here than in the central block.

A slippery dry fall is encountered about 1000 m from the mouth of the tributary canyon. Climb the fall, CAREFULLY, and proceed another 200 m to a point where the canyon walls consist of white diorite intruded by deformed mafic dikes. The diorite is another distinctive Precambrian unit in the basement complex, and in 1952 John Crowell realized that it has an identical counterpart in the north-central Transverse Ranges in Soledad Canyon near Saugus, 300 km to the northwest on the other side of the San Andreas fault. Notice the deep channels cut into the basement surface, now choked with coarse, angular detritus derived from the local metamorphic basement rocks, rather than the granitic rocks to the north and northwest that supplied most of the sediment for the overlying strata.

Return to parking area at the end of Painted Canyon road, proceed down-canyon about 500 m to the base of the Mecca Formation on the southwest side of the basement and proceed up the tributary canyon on the right (north) side of the road.

This part of the field excursion involves a somewhat rigorous hike up a steep, rubble-filled defile along the trace of the Painted Canyon fault. Excellent exposures of the fault and its gouge may be inspected. The goal is to reach the crest of the ridge where broad views may be had over the platform and central blocks (Fig. 13). We also view the relation of the basement to the sedimentary strata in the platform block, and the upper parts of the complex structure related to the Painted Canyon fault (Fig. 10). The route on top of the ridge, nicknamed Art's Hill by UCSB grad students Marty Parris and Alula Damte, traverses one of the cut-off thrust segments of the Painted Canyon fault (Fig. 14), and affords a cross-sectional view of the convex-upward geometry of the fault (Fig. 15). This hike takes about 1.5 to 2 hours, depending on the size of the group and the complexity of questions the field trip leader must answer.

Return to the floor of the main canyon, walk back up Painted Canyon into the basement where the Painted Canyon fault cuts through it. Two main strands of the fault are exposed in the canyon bottom. See the fine cross section of the fault where it separates basement from Mecca Formation in the southeast canyon wall. It separates dark gray, dominantly gneissic basement from light gray, dominantly granitic basement on the northwest wall at canyon floor level.

The mouth of another tributary canyon enters the main canyon at the Painted Canyon fault, 50 m to the right (southeast) of the road. Informally designated Little Painted Canyon by Sylvester and Smith (1976), this canyon affords excellent exposures of the "triangle zone" and the décollement that necessarily must be beneath it (Fig. 16). The walk up the canyon goes through highly fractured gneissic basement cut by orange Tertiary felsite dikes, both of which are cut by the northeast strand of the Painted Canyon fault. The buttress unconformity between basement and the Mecca Formation dips gently northeast, but the Mecca

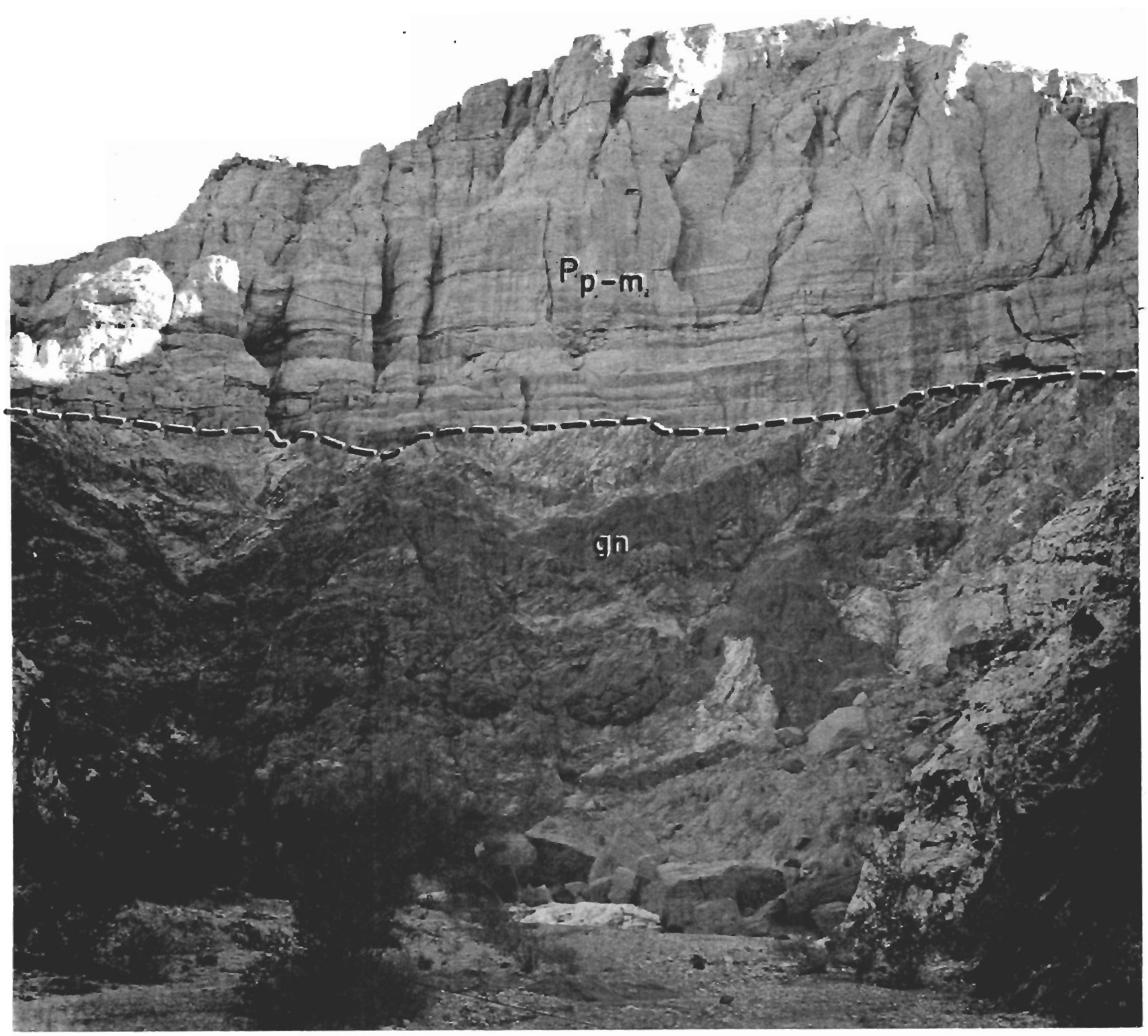


Fig. 12. Massive beds of arkose (Pp-m) lying nonconformably upon gneiss and leucodiorite (gn). Platform block, upper Painted Canyon, Mecca Hills.

Formation and the overlying Palm Spring formation dip vertically to overturned. Those vertical beds are thrust over gently folded strata in the triangle zone which here is only 5 m wide at canyon floor level (Fig. 16). A second, lower thrust fault rises from beneath the canyon floor (Fig. 16) and extends about 100 m up-canyon as a bedding plane fault before it dies out up-canyon.

Return to the main canyon and continue up-canyon to the end of the road. We walk through the basement to the buttress unconformity into vertical or overturned Mecca and Palm Spring strata and into the "triangle zone" that is exposed on both sides of the canyon (Figs. 17, 18). Notice especially the complicated arrangement of faulted folds on the northwest canyon wall that have been shoved northeastward beneath nearly flat Palm Spring Formation of the platform block (Fig. 18). A thrust slice from the central block lies upon the flat strata. The "triangle zone" is about 400 m long, 70 m wide at canyon level, and about 100 m high.

The intense folding and reverse faulting is due to the shortening associated with transpression across the entire San Andreas fault zone in the Mecca Hills. The Painted Canyon "triangle zone" is similar in structural arrangement to triangle or "delta zones" at the extremities of overthrust faults, such as along the front of the Canadian Rockies overthrust belt thrust where it rams into flat, undeformed platform strata (e.g., Bally et al., 1966), and the opposed arrangement of the Cache Creek and Hoback thrusts near Jackson, Wyoming.

* * * Conclusion of this field excursion * * *

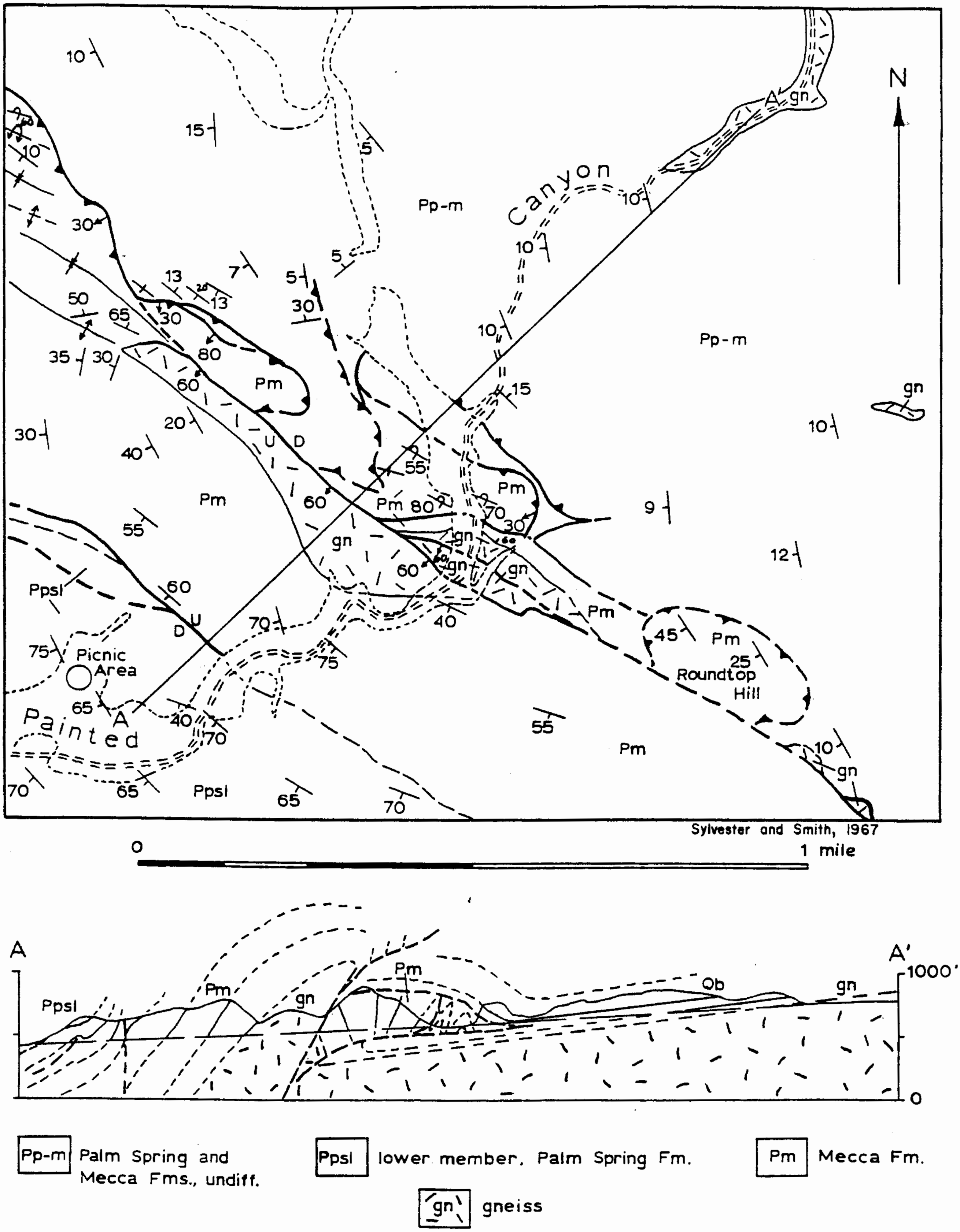


Fig. 19. Geologic map and cross section of upper Painted Canyon, Mecca Hills, Salton Trough (from Sylvester and Smith, 1976)

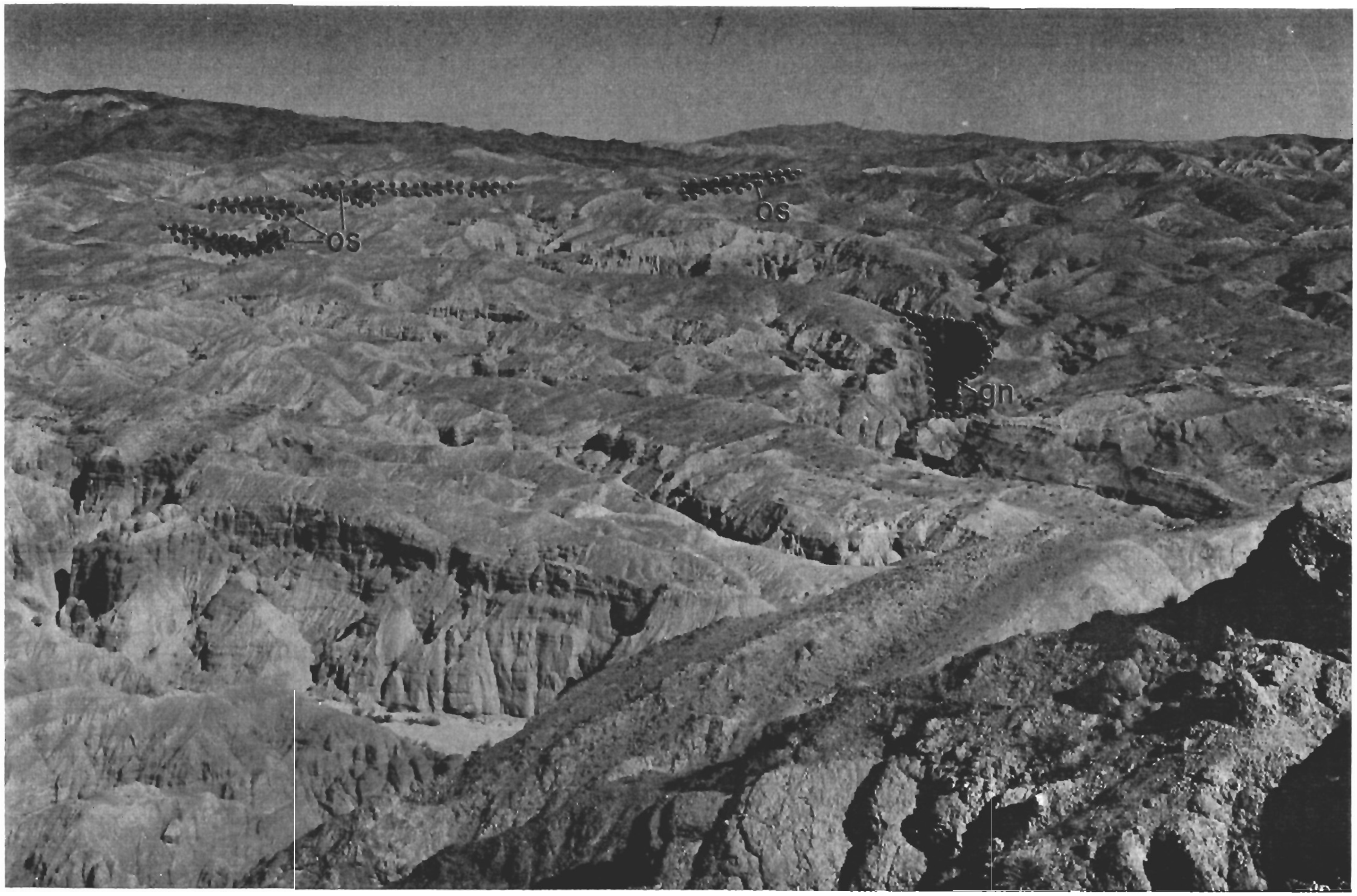


Fig. 13. View northeast across platform block from Art's Hill. The strata dip gently southwestward and were derived mainly from high Mountain terrane on skyline. Gneiss basement rocks (gn) and Orocopia Schist (os) are exposed locally in some of the deep canyons.

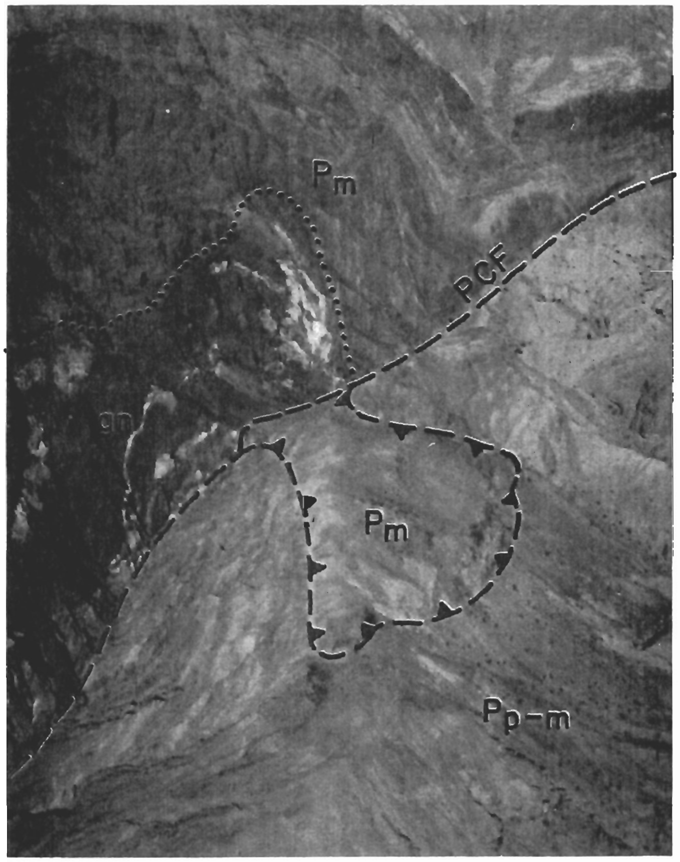


Fig. 14. Oblique aerial view west down plunge of fold axes of anticline and syncline in Mecca Formation (Pm) on hanging wall of Painted Canyon fault (PCF). Highly fractured and sheared gneissic basement (gn) is in core of anticline. Contact between basement and sedimentary strata is depositional. A klippe of Mecca Formation overlies vertical and overturned beds of Mecca and Palm Spring Formations (Pp-m).

Fig. 15. View northwest of Painted Canyon fault (PCF) from northwest end of Art's Hill. The fault, which dips 70° in the center of photograph, flattens upward to 30° on the right end of skyline ridge. Dotted lines indicate structure in the Mecca (Pm) and Palm Spring (Pp-m) formations.

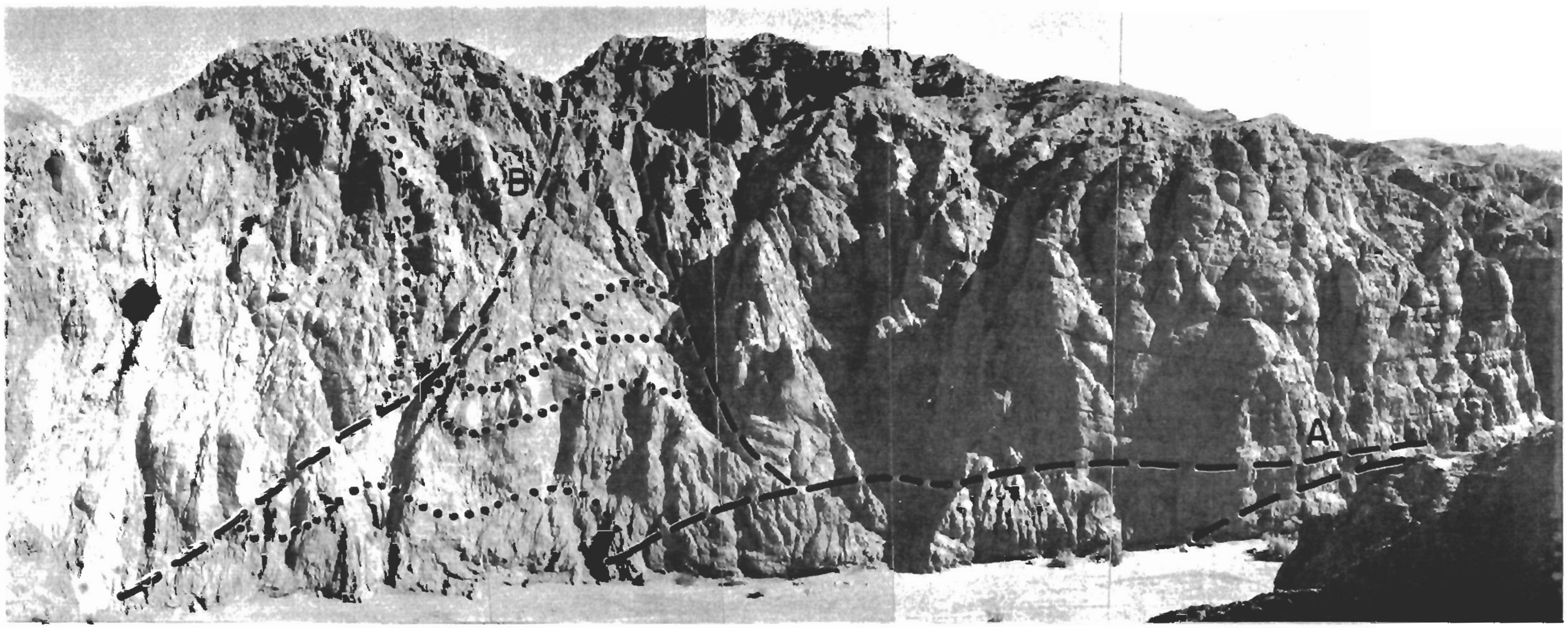


Fig. 16. View west of "triangle zone" on west wall of Little Painted Canyon. Bedding is dotted, faults are dashed. Fault A dies out into the bedding up-canyon. Fault B can be traced over the ridge to its position in Figure 17.

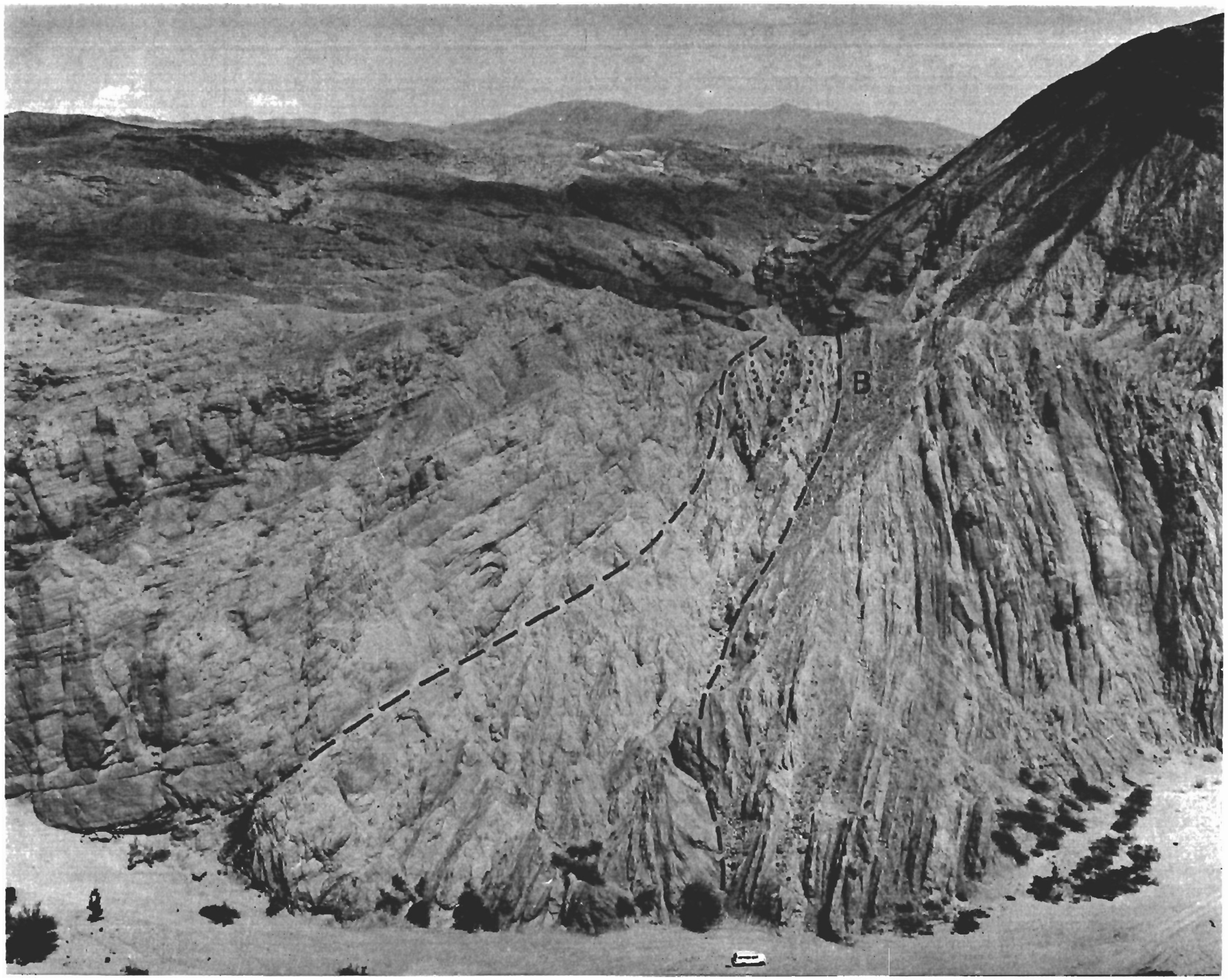


Fig. 17. View east of "triangle zone" in east wall of Painted Canyon. Bedding is dotted, faults are dashed. Taken from southeast end of Art's Hill. Truck on canyon floor indicates scale. Fault projects over the ridge to its position in Figure 16.

Fig. 18. View west of folded and faulted Palm Spring formation in footwall of Painted Canyon fault, west wall of Painted Canyon. Bedding is dotted, faults are dashed. Truck on canyon floor indicates scale.

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Structure section in Painted Canyon, Mecca Hills, southern California

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LOCATION

The Mecca Hills lie on the northeast margin of the Salton Sea astride the San Andreas fault zone near its southern terminus (Fig. 1). Painted Canyon bisects the Mecca Hills and is reached by driving 5 mi (8 km) eastward from Mecca on State Highway 195, and 0.2 mi (500 m) across and beyond the Coachella Canal, to a graded dirt road which follows a powerline northwestward 2 mi (3 km) to the mouth of the canyon (Fig. 1).

A few logistical remarks are worth emphasizing. Visitors should be aware of the hazards associated with flash floods, washed out roads, soft sand, off-road vehicles, and shooters. Temperatures soar to more than 104° (40° C) in late spring, summer, and early fall. Two plants, the smoke tree and desert holly, are protected by law and should not be disturbed. Rattlesnakes and scorpions are among the endemic fauna. Nearly all aspects of the general geology can be seen adequately from the canyon floor or can be reached by short treks up side canyons. Due caution should be exercised when climbing the friable rocks of the canyon walls. In the courses of many little canyons are abrupt, vertical dry falls, around most of which are no detours.

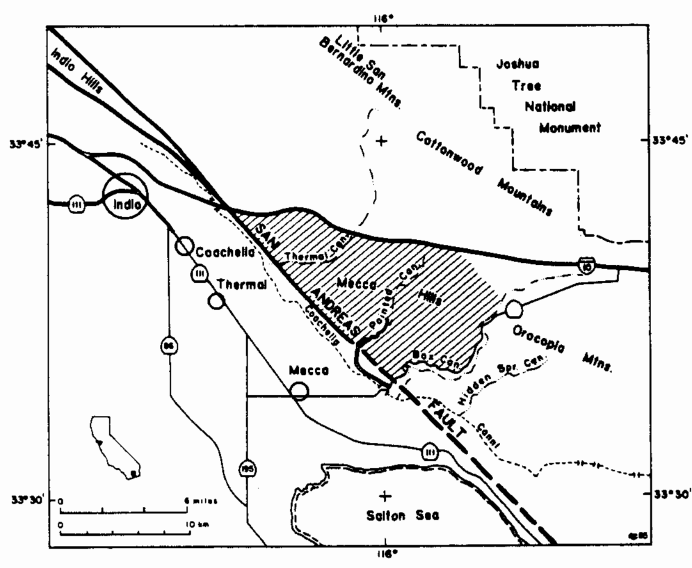

Figure 1. Index map showing the location of the Mecca Hills (ruled pattern) and Painted Canyon relative to local highways and towns.

SIGNIFICANCE

The Mecca Hills are the surficial expression of a "palm tree structure" (Sylvester and Smith, 1976), or "flower structure" in the terminology of Wilcox and others (1973). This refers to an arrangement of faults, folds and, in the case of the Mecca Hills, basement blocks, which forms as a result of convergent strike-slip faulting (Fig. 2). It is well exposed and quite accessible because basement rocks are exposed in their structural relations with the overlying sedimentary rocks, and because there is little vegetation and alluvial cover.

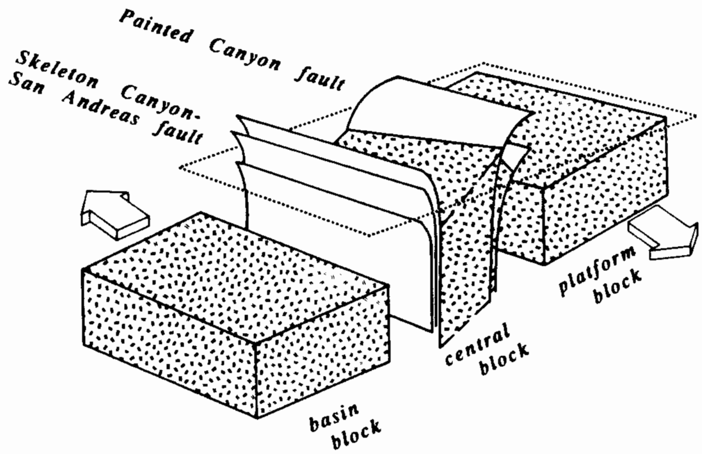

Figure 2. Idealized block diagram of the basement and principal faults in the Painted Canyon part of the Mecca Hills. Dotted parallelogram represents the surface. By permission of American Association of Petroleum Geologists.

STRUCTURAL AND LITHOLOGIC OVERVIEW

Within the part of the Mecca Hills crossed by Painted Canyon, three structural domains or blocks are distinguished by the style and degree of deformation as well as by the type and thickness of late Cenozoic sedimentary rocks; the three are informally designated the platform block, the central block, and the basin block (Fig. 2; Table 1). They are separated from one another by the Painted Canyon and San Andreas-Skeleton Canyon faults which flatten upward, carrying rocks of the central block outward upon the adjacent blocks (Fig. 3). It is this geometrical arrangement of faults relative to the three blocks which led us to designate this a "palm tree structure" (Sylvester and Smith, 1976). The structural and lithologic contrasts among the three domains are summarized in Table 1.

Basement Rocks

The basement comprises two main rock units: (1) the Chuckawalla Complex (Miller, 1944) which is chiefly Precam-

TABLE 1. LITHOLOGIC AND STRUCTURAL CONTRASTS AMONG THE THREE STRUCTURAL BLOCKS, MECCA HILLS

Basin Block	Central Block	Platform Block
	Pre-Cenozoic Basement Rocks	
Not exposed	Highly sheared gneiss and granite of the Chuckawalla Complex	Moderately sheared to unsheared gneissic and plutonic rocks of Chuckawalla Complex; Orocopia Schist
	Basement-sediment surface is steeply tilted southwestward	Basement-sediment surface gently inclined southwestward
	Cenozoic Sedimentary Rocks	
Alluvium	Arkose and conglomeratic arkose	Conglomeratic arkose and conglomerate
Thickness: 12,000-15,000 ft (3,000 5,000 m)-	Thicker stratigraphic sequence than in eastern block - approximately 5,000 ft (1750 m)	Relatively thin stratigraphic sequence (<2,000 ft or <750 m)
Structure of strata beneath alluvial cover is not known	Broad, open folds, locally appressed and overturned, with axes oblique to traces of major faults	Virtually unfolded except for minor drag folds with axes slight oblique to fault traces
	Steep, west-striking, normal faults	Steep to gently inclined, northwest-striking normal faults

brian gneiss, migmatite, and anorthosite and related rocks intruded by Mesozoic plutonic granitic rocks, and (2) the Orocopia Schist which is thought to have been regionally metamorphosed during late Mesozoic time (Ehlig, 1981). The Chuckawalla Complex is thrust upon the Orocopia Schist in the Orocopia Mountains (Crowell, 1975), but in the Mecca Hills the two rock units are separated by the high-angle Platform fault (Figs. 2, 3).

Cenozoic Stratigraphy

Late Tertiary and Quaternary nonmarine sedimentary rocks (Table 2), including intercalated alluvial fan, braided stream, and lacustrine deposits, rest unconformably upon the Precambrian basement. Stratigraphic thicknesses, age relations and correlation of various rock units across faults are not well-known in the area because of numerous depositional discontinuities, abrupt lateral and vertical facies changes, and lack of fossils and distinctive marker beds. The overall nature of the stratified sequence, however, records a period of nonmarine deposition near a tectonically active basin margin. Clast lithology and sedimentary structures show that the sedimentary detritus was derived from the Cottonwood, Little San Bernardino, and Orocopia Mountains to the northeast and east, just as it is today.

The Mecca Formation (Table 2) is the oldest unit of the Tertiary sedimentary sequence. Composed chiefly of angular, dark red-weathering detritus derived locally from the Chuckawalla Complex and Orocopia Schist, it forms a nonconformable blanket 6–15 ft (2–5 m) thick upon the basement pediment northeast of the Painted Canyon fault. It is much thicker and coarser southwest of that fault where the contact with the basement in Painted Canyon is a buttress unconformity.

The Palm Spring Formation (Table 2) marks an abrupt change in provenance in that it was derived almost entirely from a granitic terrane. Its deposition in the Mecca Hills area marks the spreading of alluvial fans from the Cottonwood and Little San Bernardino Mountains across the pediment of the platform block. Like the Mecca Formation, the Palm Spring Formation thickens abruptly across the Painted Canyon fault and is progressively finer-grained basinward. Numerous diastems within the formation southwest of Painted Canyon indicate depositional interruptions reflecting Plio-Pleistocene episodes of folding and faulting at the margin of Salton Trough. Today, in Painted Canyon, the thicker sedimentary sequence of the central block is uplifted relative to that on the platform block. Thus, apparent tectonic inversion implied by this reversal may be resolved by vertical *separation* associated with strike-slip.

STRUCTURAL PROFILE

Basin Block

Geophysical studies by Biehler, Kovach, and Allen (1964) indicate that the depth to basement ranges from 6,000 ft (2,000 m) to as much as 15,000 ft (5,000 m) beneath Coachella Valley. A steep gravity gradient across the San Andreas fault along the southwest edge of the Mecca Hills probably indicates a near-vertical step of the basement of at least 12,000 ft (4,000 m). Thus, the San Andreas fault is the principal structural boundary between the Salton Trough and the high-standing terrane to the northeast in the Mecca Hills.

A thin strip of sedimentary rocks is upturned along the northeast edge of the basin block. Comprising distal fanglomerate

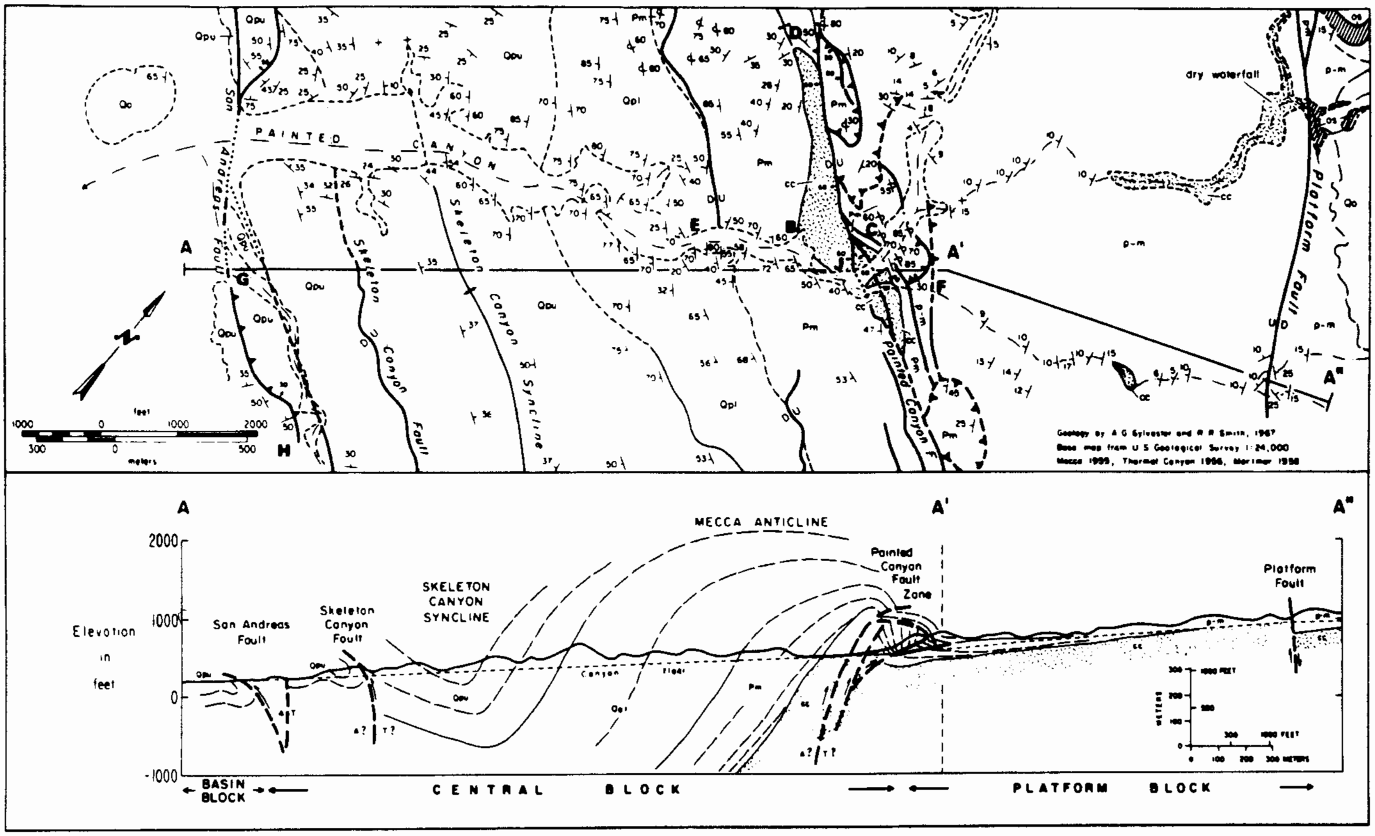

Figure 3. Geologic strip map and structural cross section parallel to Painted Canyon in the Mecca Hills. Letters B–J are localities referred to in the text. Stippled pattern is Chuckawalla Complex basement; ruled pattern is Orocopia Schist.

and lacustrine equivalents of the Palm Spring and younger Ocotillo Formations, the strata are strongly folded, especially southeast of the mouth of Painted Canyon. Here, fold axes trend west-northwest, oblique to the strike of the San Andreas fault, and locally plunge up to 70° in the same direction (locality H in Fig. 3).

Nearly monolithologic beds of Orocopia Schist clasts in the base of the Ocotillo Conglomerate (Pleistocene) show that these strata have been displaced right-laterally at least 15 mi (22 km) from their source in the Orocopia Mountains (Ware, 1958).

San Andreas–Skeleton Canyon Fault Zone

The southwest side of the central block is bounded by a complex zone of faults and folded sedimentary rocks. At the mouth of Painted Canyon, the relatively low structural and topographic relief precludes good exposures of these structures, but they may be studied in Skeleton Canyon, a major tributary marked by low hills of brick-red, phacoid-bearing fault gouge of the San Andreas fault on the southeast side of Painted Canyon (locality G in Fig. 3). The faults are steep in the bottoms of

TABLE 2. THICKNESSES, AGES, AND LITHOLOGY OF CENOZOIC FORMATIONS, MECCA HILLS (after Dibblee, 1954)

Formation	Lithology
Canebrake-Ocotillo Conglomerate (Pleistocene) 0-5,000 ft (0-750 m)	Gray conglomerate of granitic debris in central Mecca Hills, reddish conglomerate of schist in eastern Mecca Hills
Palm Spring Formation (Pliocene and Pleistocene) 0-4,800 ft (0-1,200 m)	Upper member: thin-bedded buff arkosic sandstone, grading basinward into light-greenish sandy siltstone. Lower member: thick-bedded buff arkosic conglomerate and arkose with thin interbeds of gray-green siltstone
Mecca Formation (Pliocene) 0-800 ft ((0-225 m)	Dark reddish brown arkose, conglomerate, claystone; chiefly metamorphic debris in basal strata

canyons, and they flatten upward on the sides of the canyon walls. Locally, tight and nearly vertical folds are beneath low-angle segments of the gouge zones, such as at locality H.

The most recently active trace of the San Andreas fault is marked northwest of Painted Canyon by aligned gulches and ridge notches, deflected stream courses, fault gouge, nearly vertical shear surfaces with horizontal slickensides, and en echelon fractures and fault scarps in alluvium (Clark, 1984). Interpretations of several of these features are complementary and consistent, indicating right-slip movement with local vertical uplift.

Central Block

The central block is a 1 mi (1.5 km)-wide, northwest-trending zone of broad, open folds and relatively minor, high-angle faults, bounded by the Painted Canyon and San Andreas faults (Figs. 2, 3). Northwest of Painted Canyon, the axial traces of most folds trend about N70°W and define a step-right en echelon pattern. However, the folds are appressed—overturned in some instances—and trend parallel to, or are truncated by the Painted Canyon and San Andreas faults. The largest and most prominent of these folds is the Mecca anticline which forms the topographically highest part of the hills northwest of Painted Canyon. The slivers of basement exposed along the Painted Canyon fault represent the core, and are structurally the deepest exposures of the anticline.

The lower part of Painted Canyon, in the central block, is a structural depression exposing a thick, nearly flat-lying sequence of sandy siltstone and silty sandstone (upper member of Palm Spring Formation) in the trough of the shallow Skeleton Canyon syncline (Fig. 3). As one proceeds up the canyon, the stratigraphic progression is downsection into increasingly steeper tan sandstone and pebbly sandstone strata with thin, gray beds of micaceous siltstone (lower member of Palm Spring Formation) on the south flank of Mecca anticline.

A small anticline and syncline are prominently exposed in the northwest wall of Painted Canyon at locality E (Fig. 3). They are relatively minor structures and are not shown on the map because they are so small and die out laterally and vertically in very short distances: they do not project across the canyon to the southeast wall and are only gentle flexures in the next canyon to the northwest. These folds and others similar in style and position along the flank of the anticline formed in response to layer-parallel shortening in the fold limb shared by Mecca anticline and Skeleton Canyon syncline.

Painted Canyon probably received its name from the varicolored exposures of basement rocks and overlying Mecca Formation in the central part of the canyon around localities B, J, and C in Figure 3. There, dark migmatitic gneiss, intricately intruded by small, irregularly-shaped bodies of white granitic rocks of Mesozoic age, and light orange and yellow felsite dikes (K-Ar age of about 24 m.y.), is overlain by a very coarse, bouldery facies of dark red-brown-weathering Mecca Formation. The contact is a low-angle buttress unconformity that is best observed on the west wall of the canyon at locality B, where it dips 60° to the southwest. The contact and overlying beds form the core of the northwest-plunging Mecca anticline at locality D. There the northeast limb of the anticline is truncated by the Painted Canyon fault; elsewhere, however, structurally higher parts of the northeast limb are overturned and thrust short distances upon the platform block (locality C, Fig. 3).

In contrast to the relatively unsheared basement in the platform block, the basement in the anticline at locality D and adjacent to the Painted Canyon fault, such as at locality J, is pervasively fractured and sheared into a granulated mass of rock fragments ranging typically from 0.5 cm to 5 cm in diameter. The degree of fracturing is highest next to the fault. The overlying sedimentary rocks, however, are strongly fractured only within a meter or so of the fault surface; the basement-sedimentary rock contact is not a surface of slip. These field observations show that in response to contractile strain, the basement adjusted cataclastically by slip on old fractures and shear surfaces that we assume formed during a long history of pre-Mecca Formation deformation in the San Andreas fault zone; the sedimentary cover responded to deformation at the basement level by folding passively, partly by intergranular slip and partly by flexural slip concentrated in thin mudstone and siltstone beds. This mechanism is analogous to passive warping of a pliable material over a deformed mass of buckshot.

Painted Canyon Fault

The Painted Canyon fault is a major structural discontinuity at least 15 mi (24 km) long and is defined by a zone of crushed rock and fault gouge from a few centimeters to several meters wide. The fault surface dips as steeply as 70° in canyon bottoms, and it flattens upward to nearly horizontal attitudes beneath slabs of the central block that have been carried up to 330 ft (100 m) out, over the southwest edge of the platform block (locality C, Fig. 3). Beneath the low-angle segments, footwall strata of the platform block are dragged abruptly to vertical and overturned attitudes. Right horizontal separation on the Painted Canyon fault is about 2 mi (3 km), whereas the vertical separation of the basement-Mecca Formation contact locally exceeds 490 ft (150 m).

The geometry of Painted Canyon fault and of its associated structures is displayed best in the walls of central Painted Canyon as shown diagrammatically in Figure 4. In general, the structure is a faulted anticline in the hanging wall and an overturned syncline in the footwall, but it is a structure in which the two fault blocks are juxtaposed by a fault having about 2 mi (3 km) of right separation. The contact between the Mecca Formation and the crushed migmatite basement in the footwall is also a buttress unconformity, but it is tilted northeastward almost 90° from its initial gentle southwest dip (Fig. 4, see esp. section A-A′). A sequence of beds in the overturned syncline is buckled between older and younger strata in the way that the pages of a flat-lying book might be shoved and folded between their covers. The buckled beds are bounded by a triangular arrangement of high- and low-angle faults that are best observed in Little Painted Canyon at locality F (Fig. 3). The thrust faults and associated folds are additional manifestations of contraction and uplift of parts of the central block with respect to the platform and basin blocks in transpressional deformation.

Platform Block

The upper part of Painted Canyon is incised into the northeastern structural domain: the platform block. Nearest the Painted Canyon fault, the basement rocks are overlain nonconformably by strata of the Mecca and Palm Spring Formations that are much thinner, and typically composed of coarser and more angular detritus, in this block than in the central block. The contact is a nearly planar, pre-Mecca Formation erosion surface into which channels up to 16 ft (5 m) deep were incised and filled with locally-derived, very coarse and angular Mecca Formation detritus. The erosion surface and overlying strata dip gently southwestward when mapped from canyon to canyon. Except for faulting and minor drag folds adjacent to the faults, however, strata on the platform block are undeformed.

The dry waterfall prevents further access up the canyon by motor vehicle. Near it (Fig. 3) is the best place to observe the relatively undeformed character of the basement and overlying sedimentary rocks, the details of the nonconformable contact, and the geometry of subsidiary faults and associated minor drag folds. The dry waterfall is cut into migmatite of the Chuckawalla Complex that is massive and relatively unfractured in contrast to that in the central block. Smooth and contorted flow folds in the migmatite are products of high temperature and pressure-ductile deformation in Precambrian time. About 660 ft (200 m) up the canyon from the dry waterfall are exposures of anorthosite and related rocks that Crowell and Walker (1962) described and correlated with similar rocks on the west side of the San Andreas fault in the Transverse Ranges. Farther up the canyon, these and other rocks of the Chuckawalla Complex are juxtaposed against the Orocopia Schist by the high-angle Platform fault (Fig. 3). Nearly horizontal slickensides show that the latest movement on that fault was horizontal, but drag folds with nearly horizontal axes indicate that a significant component of vertical displacement has occurred as well.

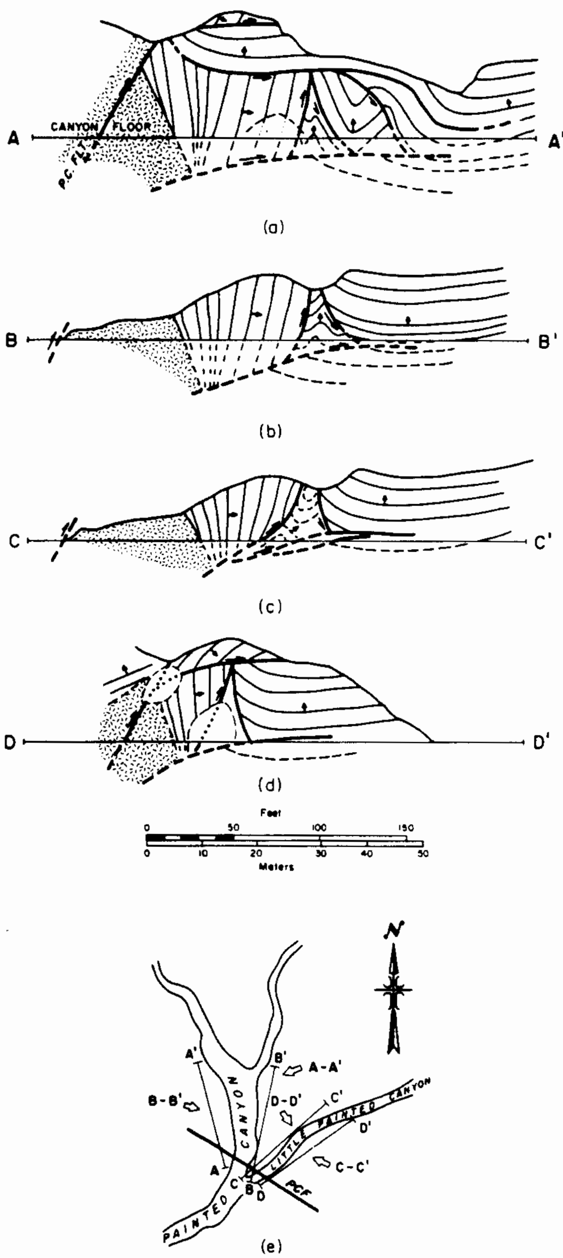

Figure 4. Generalized cross-sections of buckled strata and low- to high-angle faults in the footwall of the Painted Canyon fault. (a) Northwest wall, Painted Canyon; (b) southeast wall, Painted Canyon; (c) northwest wall, Little Painted Canyon; (d) southeast wall, Little Painted Canyon; (e) index map showing locations of cross sections. In (a), (b), (c) and (d) arrows indicate tops of beds. In (e) open arrows indicate locations of view points and view directions for each cross section.

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The following 1:250,000-scale geologic maps in southern California show the Mecca Hills and their relation to the regional geology:

Jennings, C. W., 1967, Salton Sea sheet; Geologic map of California (Olaf P. Jenkins edition): California Division of Mines and Geology.

Rogers, T. H., 1965, Santa Ana sheet; Geologic map of California (Olaf P. Jenkins edition): California Division of Mines and Geology.

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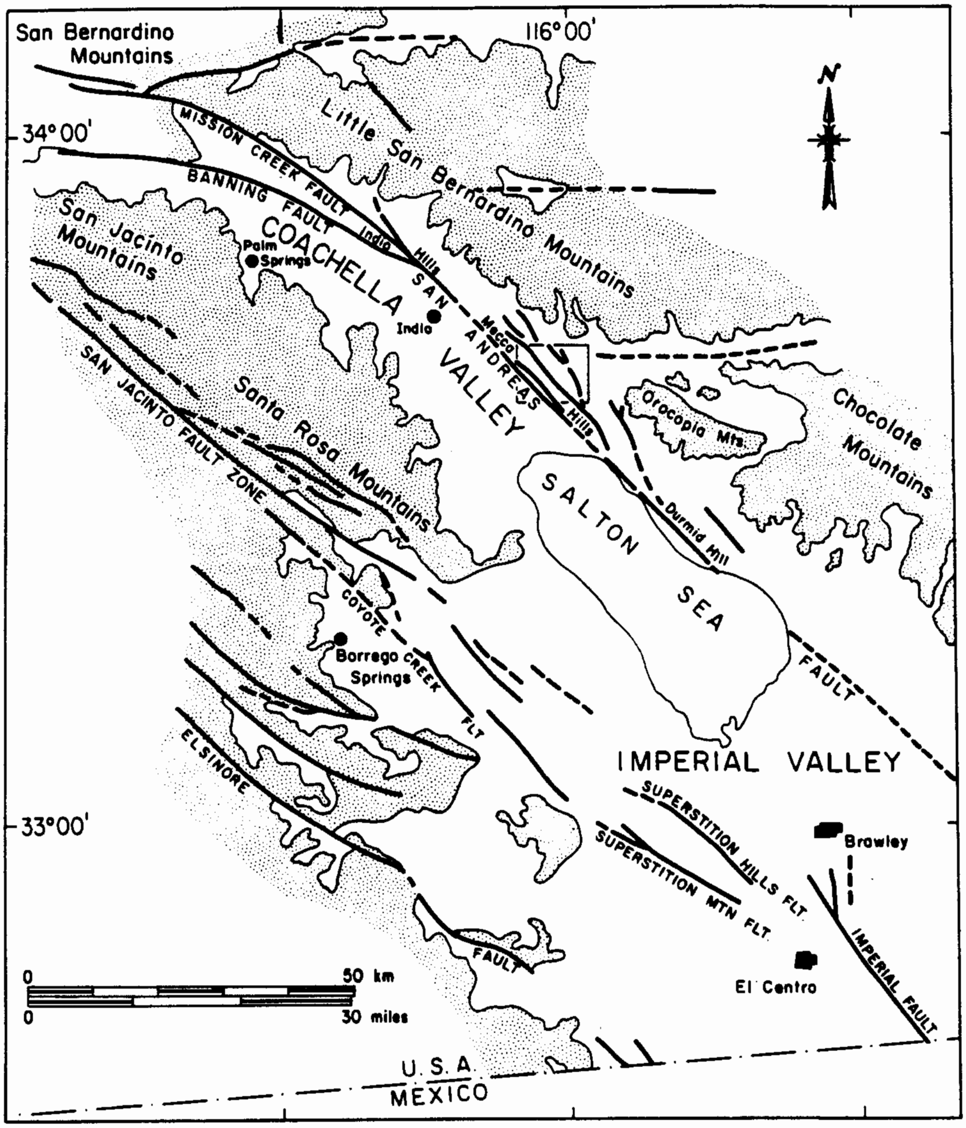

Map of the Salton Trough showing principal faults, mountainous areas underlain by pre-Cenozoic crystalline rocks (stippled), Tertiary and Quaternary sedimentary rocks (no pattern), and main towns. The polygon across the San Andreas fault zone north of the Salton Sea outlines the mapped area of the Mecca Hills.

BOX CANYON STOPS

LOCATION: State Highway 195, Mecca Hills, Salton Trough

STRATIGRAPHY	AGE	FORMATIONS	FACIES
	Quaternary	Ocotillo	fanglomerate
	Plio-Pleistocene	Palm Spring	fanglomerate, lacustrine
	Mesozoic	Orocopia Schist	basement

STRUCTURE	AGE	FEATURE/STYLE
	Pliocene to present	folds, faults in strike-slip fault zone

KEY FEATURES TO OBSERVE

- buttress unconformity between Palm Spring Formation fanglomerate and Orocopia Schist
- nearly horizontal slickensides on Hidden Springs fault surface
- white, fluvial delta sandstone beds in coarse, fanglomerate
- interformational folds in siltstone sequence between thick sandstone beds
- tight synclines, broad anticlines
- diastems between upper and lower members of the Palm Spring Formation
- folded and overturned strata against the Skelton Canyon fault
- normal and reverse fault separations in cliff face of Ocotillo fanglomerate

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PAINTED CANYON STOP

LOCATION: Salton Trough, Mecca Hills, west of Hwy 195 between Interstate 10 and Hwy 111

STRATIGRAPHY	**AGE**	**FORMATIONS**	**FACIES**
	Recent	Ocotillo	alluvial fan
	Plio-Pleistocene	Palm Spring	fluvial, lacustrine, alluvial fan
	Mio-Pliocene	Mecca	fluvial, alluvial fan
Basement rocks			
	Tertiary	felsite dikes	
	Mesozoic	granite	
		Orocopia Schist	
	Proterozoic	gneissic complex	

STRUCTURE	**AGE**	**FEATURE/STYLE**
	Pliocene to present	folded, faulted block of basement and Tertiary sedimentary rocks squeezed up between San Andreas and Painted Canyon faults

KEY FEATURES TO OBSERVE

- palmtree-structure of Mecca Hills
- faults, steep at depth, flatten upward
- thin, unfolded sequence of strata on platform block vs thick, highly deformed sequence in central block between faults
- folded basement nonconformity
- tight folds bounded by triangular arrangement of faults beneath the Painted Canyon fault

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Sylvester, A. G., and R. R. Smith, 1976, Tectonic transpression and basement-controlled deformation in the San Andreas fault zone, Salton Trough, California. American Association of Petroleum Geologists Bulletin 60 (12), 2081-2102.

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