SALTON TROUGH TECTONICS CROWELL & SYLVESTER

TECTONICS OF THE JUNCTURE BETWEEN THE SAN ANDREAS FAULT SYSTEM AND THE SALTON TROUGH, SOUTHEASTERN CALIFORNIA

Edited by
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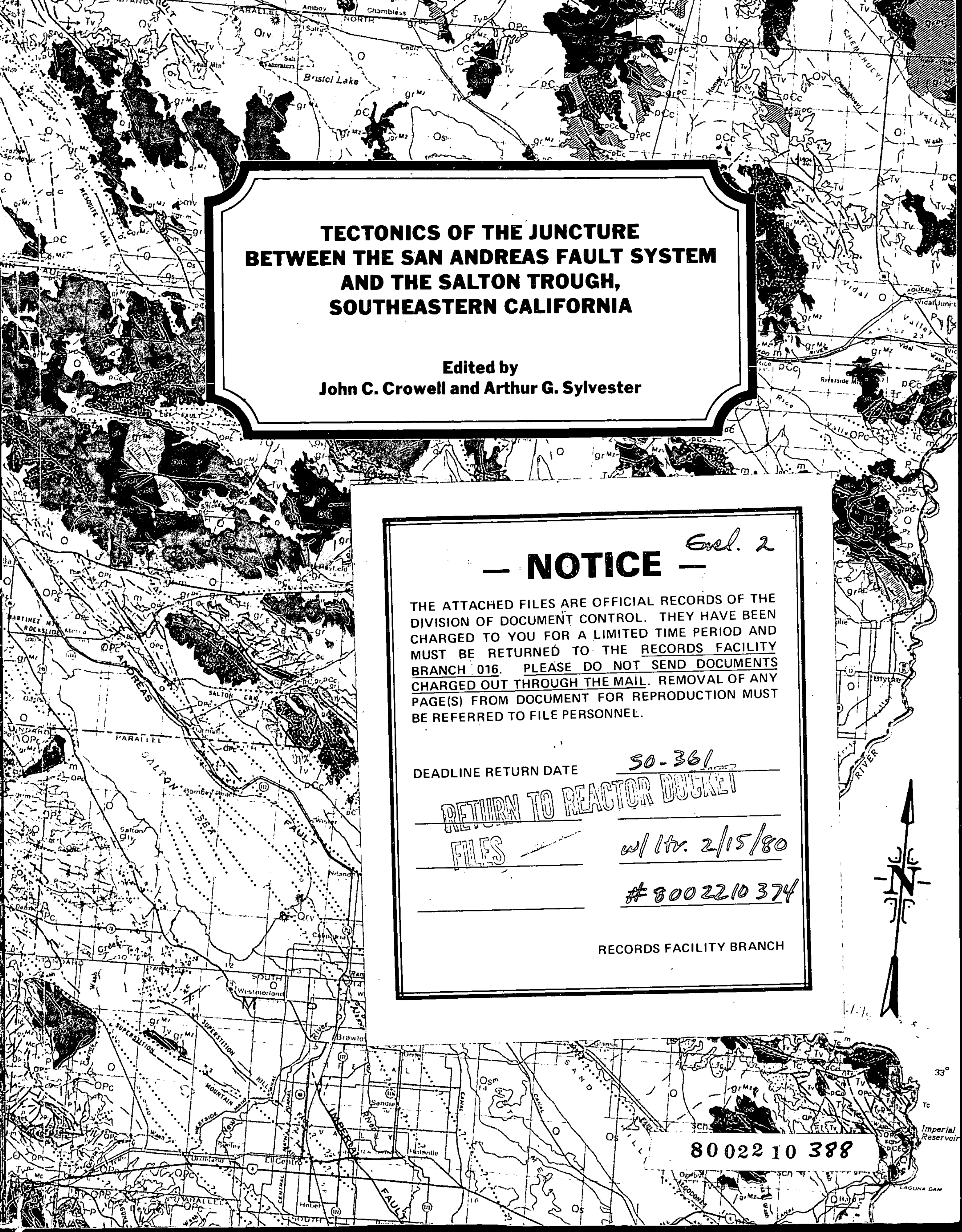

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TECTONICS OF THE JUNCTURE BETWEEN THE SAN ANDREAS FAULT SYSTEM AND THE SALTON TROUGH, SOUTHEASTERN CALIFORNIA

------------------- A GUIDEBOOK -----------------

Edited by

John C. Crowell and Arthur G. Sylvester
Department of Geological Sciences
University of California, Santa Barbara
CA 93106

Published by the Department of Geological Sciences, University of California
Santa Barbara, CA 93106

For the

Annual Meeting
Geological Society of America
San Diego, California

November 1979

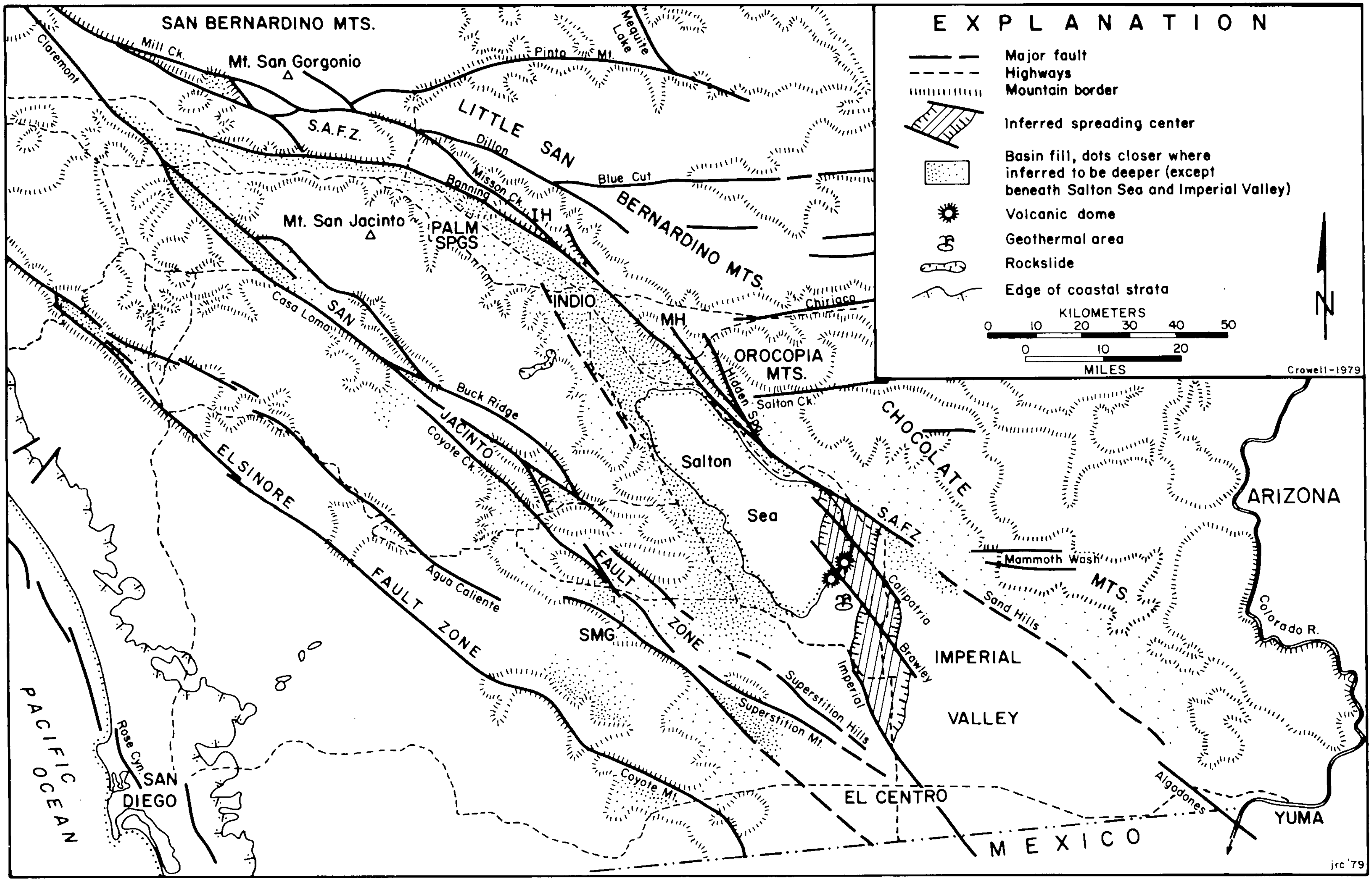

Fig. 1. Diagrammatic fault map of central Peninsular Ranges and Salton Trough region. The map shows the major faults of the San Andreas system near their juncture with the divergent plate boundary in the Salton Trough. Basin fill is indicated by stippling, and inferred active spreading centers by the line pattern SE of the Salton Sea. Abbreviations: IH, Indio Hills; MH, Mecca Hills; SMG, Split Mountain Gorge.

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PREFACE

This series of articles, ending with a guide, has been prepared on the occasion of a three-day field trip conducted at the time of the 1979 Annual Meeting, Geological Society of America, in San Diego, California. The region is noteworthy geologically because much structure, geomorphology, and many rock types are on display in the barren desert. We take delight in showing the region to our colleagues and in attempting to explain how complex local details seem to fit into a broad plate-tectonic scheme. We hope that you will enjoy visiting the region briefly as much as we have in working in it from time to time over the years.

By way of review and preparation, we conducted a graduate seminar with field trips during the spring quarter, 1979. Members of the seminar were Brian Baca, Michael Bonkowski, Barry Keller, Vincent Ramirez, Thomas Rockwell, and Richard Terres. Each student specialized in an aspect of the regional geology that interested him and wrote a term paper aimed for inclusion in this guidebook. These term papers are included here, but in most cases rewritten by one of us. In addition, we have called on Dennis Kerr, Russell Korsch, Steve Pappajohn, Gary Peterson, and Robert Sydnor for contributions. We thank all for their help.

Although we both have had experience in the region over the years, we are indebted deeply to many geologists who have written about it. Their work is acknowledged by means of the references cited. We extend particular thanks to Charles W. Jennings, California Division of Mines and Geology, for permission to publish parts of the Geologic Map of California on the cover of this guidebook. We also thank sincerely Dr. Patrick L. Abbott, Department of Geological Sciences, San Diego State University, the Field Trip Chairman for the GSA Annual Meeting. He and his helpers arranged for buses, meals, overnight stops, and other logistical matters in connection with the GSA Field Trip. James Coss has done the drafting, Cherie Topper has aided in bibliographic matters, and Virginia Gibson has done the camera-ready typing.

Additional copies of this guidebook may be obtained by writing Departmental Secretary, Department of Geological Sciences, University of California, Santa Barbara, California, 93106, enclosing payment of $12.00 for each copy. The price includes California sales tax, handling, and postage.

Santa Barbara
November 1979

John C. Crowell
Arthur G. Sylvester

Chapter 1

INTRODUCTION TO THE SAN ANDREAS-SALTON TROUGH JUNCTURE

by

John C. Crowell and Arthur G. Sylvester

ABSTRACT

Southeastern California manifests great crustal mobility where the topography is the result of tectonic activity today and in the recent past. Relations between tectonics and sedimentation are especially clear in the Salton Trough region, where sedimentation is controlled by the rugged topography and the influx of sediments coming from the Colorado River and its immediate ancestors. The crustal mobility involves great right-slip of more than 300 km during the last 8 or 10 m.y. In addition to vertical movements, a picture is emerging where crustal blocks are displaced largely sideways at the plate juncture, but are also fragmented and tip and rise and fall. Where squeezed upward in the scheme, high mountains result, and where depressed, basins are formed in which sediments accumulate.

The region extending across the Salton Trough, where it meets the San Andreas fault system coming in from the northwest, is broadly arched so that the bordering ranges stand high above the deep graben of the divergent plate boundary between the Pacific and North American plates. On the west, the northern Peninsular Ranges consist of a series of slightly tilted fault blocks separated by through-going right-slip faults, including the San Jacinto and Elsinore. These faults display elongate pull-apart basins along their trend, and where they meet the Salton Trough on the southeast, they are splayed and braided. They are inferred to meet spreading centers at the divergent plate boundary beneath a thick filling of Late Cenozoic sediments within the Salton Trough. The San Andreas fault itself extends southeastward into the region through San Gorgiono Pass on the northwest, and dies out at present at the edge of one of these spreading centers near the southern end of the Salton Sea. Structural details along the San Andreas fault zone are especially well displayed in the Indio, Mecca, and Durmid Hills along

the northeastern margin of the Salton Trough. The field excursion will be largely concerned with examining many of these features briefly, and discussing their origin and tectonic setting. The region purports to reveal much concerning the details at such a plate-tectonic juncture.

INTRODUCTION

One of the few places upon the continents today where we can observe directly the joining of a divergent plate boundary with a system of transform faults is in the vicinity of the Salton Trough in southern California. Here, at the complex northwestern end of the Gulf of California, pre-existing continental rocks of many different types and ages have been rifted and sliced and broken as the crustal segments join the San Andreas system of major strike-slip faults. These faults reach on northwestward through California to join, in turn, the Mendocino Fracture Zone and other major structures of the Pacific Floor.

A purpose of this guidebook, and of the field excursion for which it is written, is to review and to view knowledge of the tectonic history at the San Andreas-Salton Trough juncture. Another special purpose is to describe briefly the basic elements of crustal behavior at such a juncture, that is, to generalize from our perception of the tectonic evolution of this juncture to a picture of the way such junctures behave elsewhere and have behaved in the geological past.

REGIONAL SETTING

The guidebook and excursion are concerned with parts of several geographic and tectonic provinces including, from southwest to northeast, the Peninsular Ranges, the Salton Trough and Colorado Desert, the Transverse Ranges, and Mojave

Desert. The northern Peninsular Ranges lie west of the Salton Trough and consist of a series of west-tilted blocks, broken by northwest-trending fault valleys. Summits of peaks upon the blocks between the major faults rise in general eastward or northward to culminate in Mt. San Jacinto (El. 3,288 m or 10,786 ft). The tectonic tilting shows up well where old erosion surfaces with west-flowing drainage systems are conspicuous. For example, parts of the northern sector make up the Perris Surface, an ancient deeply eroded peneplain.

The east edge of the Peninsular Ranges drops off sharply along an irregular escarpment to the Salton Trough. At places this escarpment follows active faults, but at others it has been eroded back to form an irregular but still impressive mountain wall. Upland surfaces and the generalized topography of the Peninsular Ranges, therefore, rise systematically but irregularly from the Pacific Ocean on the west to the sharp drop-off into the Salton Trough on the east.

The alluviated floor of the Salton Trough is largely below sea level with the surface of the Salton Sea today at an elevation of minus 71.6 m (-235 ft). The Salton Sea, which was formed when the Colorado River burst levees between 1905 and 1907, maintains its level within a few meters through the balance between influx from irrigation waters and evaporation in the desert climate. The salinity of the Salton Sea now is about 44°/00 (ocean water has a salinity of about 35°/00).

The sea divides the long and narrow Salton Trough into two parts. The northwestern part is the Coachella Valley, fed primarily by the Whitewater River, and contains the cities of Indio and Palm Springs. The second part, the Imperial Valley, lies south of the Salton Sea and is largely below sea level. Farther south near the International Boundary the floor of the valley slopes gently upward to cross the broad apex of the Colorado River delta. Today the Colorado River flows southward from Yuma along the eastern flank of this broad fan-delta, and if it were not for the activities of man, it would flow into the head of the Gulf of California. A large proportion of its water, however, is taken off for use by the City of Los Angeles and now reaches the Pacific Ocean largely through the Hyperion Sewer Outfall near the Los Angeles International Airport (LAX). A great deal is also used for irrigation in the Imperial Valley, and some by Mexico through treaty agreements.

The northeastern wall of the Salton Trough is marked by a chain of desert ranges, from northwest to southeast: the Little San Bernardino, Cottonwood, Orocopia, Chocolate, and Cargo Muchacho Mountains. Summits along this crest locally exceed 1,500 m (4,920 ft) but most are less than about 1,000 m

(3,280 ft). Ranges of low hills lie below the northeastern margin and well within the Salton Trough. These include the Indio, Mecca, and Durmid Hills, and the Algodones San Dunes. The Little San Bernardino Mountains constitute the east end of the Transverse Ranges, whereas the other ranges form the first of many in the Colorado Desert and on beyond into the Mojave Desert Province.

The San Gorgonio Pass region at the northwest end of Salton Trough marks the terminus of Salton Trough as well as the rift of the Gulf of California. The pass is guarded on the north by Mt. San Gorgonio (Greyback - El. 3,506 m or 11,502 ft) and by Mt. San Jacinto (El. 3,288 m or 10,786 ft), two of the highest three peaks in California south of the Sierra Nevada. The alluviated pass between them has elevations of about 800 m (3,200 ft) and provides access to the San Bernardino and Los Angeles areas. It is within the region of San Gorgonio Pass that the true juncture between the San Andreas fault and the Salton Trough is located.

The Salton Sea geothermal region is entirely within Pliocene and Quaternary sediments of the Colorado River delta at the south end of the Salton Sea. At the time of deposition these sediments consisted of sand, silt and clay of uniform original mineralogical composition, but under the elevated temperatures and pressures of the geothermal system they are being transformed to low-grade metamorphic rocks of greenschist facies (Muffler and White, 1969; Elders and others, 1972; Robinson, Elders, and Muffler, 1976). Temperatures within the explored geothermal system range up to 360°C at 2,200 m (7,100 ft). The wells produce a brine containing over 250,000 ppm (mg/l) of dissolved solids, primarily compounds of chlorine, sodium, calcium, potassium, and iron together with a host of minor constituents.

Concentrated brine tapped by a deep well drilled for geothermal power near the Salton Sea in California deposited metal-rich siliceous scale at the rate of 2/3 tons/month. This iron-rich opaline scale contains an average of 20 percent copper and up to 6 percent silver present in bornite, digenite, chalcopyrite, chalcocite, stromeyerite, and native silver. The heavy metals in solution greatly exceed the sulfur content, on a modal basis. They are apparently derived from the sediments of the brine reservoir, being released from the silicate minerals in which they occur in trace amounts as metamorphism of the sediment proceeds.

CRUSTAL MOBILITY

The contrasting topography today, ranging from high peaks to depressions below sea level, is clearly the result of active tectonics. As humans we are impressed with the topographic relief and the contrast in climate among the temperate coastal belt, the pine-covered high ranges, and the extremely arid desert lying in the rain shadow down air flow behind the barrier of the Peninsular Ranges. Geologic understanding, however, is leading us to realize that much of the obvious vertical movement responsible for this varied terrane is accompanied by horizontal tectonic movements that are many times greater in magnitude.

Although the region of the Salton Trough-San Andreas juncture has been under study by geologists for nearly a hundred years, it is only within the last two decades that evidence pointing toward large-scale horizontal tectonic movements has slowly accumulated (Crowell, 1960; 1962). Rocks exposed in the Orocopia Mountains northeast of the fault, for example, have their counterpart in the north-central Transverse Ranges southwest of the fault, requiring right-slip on the San Andreas fault system of about 300 km. In recent years more and more evidence confirming this magnitude of displacement has accumulated (Crowell and Walker, 1962; Crowell, 1975a; Ehlig and Ehlert, 1972) with little to deny it (Baird and others, 1974). Studies elsewhere in California of both geology and neotectonic history require great horizontal mobility to the northwest (Crowell, 1952; Hill and Dibblee, 1953; Addicott, 1968; Huffman, 1972; and many others). With the birth of the concept of transform faulting and plate tectonics (Wilson, 1963) and the application of these concepts specifically to the San Andreas fault by Vine and Wilson (1965), the relationships of these 300 km movements to continental drift and a global tectonic scheme began to clarify.

Geologists are now at a state where they are both trying to fit the tectonic details of the San Andreas-Salton Trough region to the concept of plate tectonics and trying to test the theory itself. Although the general applicability of plate-tectonic concepts to the region has been nicely pointed out by Atwater (1970) the details still require careful elucidation. At the time of this writing, we believe strongly that the theory of plate tectonics applies to Salton Trough, but the region is one of plate-margin fragmentation, jostling, tilting, and rotation. These processes are superposed on the gross plate tectonic scheme and modify it in detail. The region is an ideal one in which to study these complexities in order to arrive at better understanding of how crustal plates behave at such a juncture. One purpose of this guidebook and excursion, therefore, is to describe and to view some of the results of these types of plate-margin activity, and to see how this activity fits in and modifies present understanding of plate-tectonic processes.

The crux of arriving at tectonic understanding seems to involve an appreciation of crustal mobility and flexibility both vertically and horizontally. As blocks of terrane have moved laterally--a manifestation of continental drift--they have moved upward, downward, and also nearly horizontally. With convergence between major strike-slip faults, some blocks have been squeezed upward to make high-standing mountain ranges which, in turn, have provided source areas for sediments (Crowell, 1974b). Where faults have diverged, crustal blocks have sunk to make local sites for the accumulation of sediments, and the nature of those sediments reveal much concerning tectonic activity. The opening of the Gulf of California has resulted in a sharp cleft within continental rocks, one that is now functioning as a divergent plate boundary, so that a series of depositional sites for sediments has formed (Hamilton, 1961; Moore, 1973). En echelon spreading centers arranged with transform faults characterize its floor (Lomnitz and others, 1970; Elders and others, 1972). Some of these transforms are confined to new oceanic crust believed to be forming as floor beneath the sediments of the Gulf and part of the Salton Trough; others crack landward and extend into the San Andreas system cutting continental terrane (Crowell, 1974a).

In summary, the Salton Trough is a complex pull-apart where the western wall is moving relatively northwestward away from the continent of North America. But we picture this movement as far from sharp and clean; instead blocks sag and collapse into the growing rift, and tilt and rotate and slide about in the process. Moreover, the terrane to the west beyond the rift is fragmented into long slices that are carried northwestward with the Pacific plate. They move much like ice floes riding upon a current, but their shapes are irregular so that at places the crustal slices collide and jostle and tip as they ride upon their neighbors. Elsewhere they pull apart to make elongate holes. But this ice-floe analogy is a gross simplification, for the crustal blocks are far more flexible and deformable than brittle blocks of ice. The tectonic blocks stretch and fold and tip and contract as well as splinter. On our excursion we will point out evidence that we think supports such a model of mobility and seek discussion either for or against such an interpretation. At places we informally refer to this as "porpoise structure" in order to emphasize the rise and fall through time of blocks along the major strike-slip faults. For example, long slices within braided fault zones, as movement continues, may first rise high and then sink low--first providing a source for sediment, and then a site for sediment deposition. We draw an analogy to this structural process and a porpoise swimming parallel to the fault strike, arching above the sea surface and then diving below (Fig. 2).

Such a picture of the tectonic behavior of the region seems to apply at present and back in time for about four million years, but rocks older than this have been subject to movements and deformations of perhaps quite different types and orientations. Western North America has been at or near a lithospheric boundary more or less continuously back in time as far as we can read the record. One tectonic style has been overprinted upon an older one and perhaps several older ones. So the concept of tectonic overprinting must also be kept in mind. For example, California was the site of a convergent plate boundary until Mid-Tertiary time when a transform boundary replaced it. One set of rock types and tectonic styles was then replaced or superposed upon the older, further complicating interpretation.

WORKING WITH STRIKE-SLIP FAULTS

In working with major strike-slip faults and with these concepts, it is essential to keep some basic principles of fault geometry in mind. A clear distinction between the geometry of slip and separation is of paramount importance. Slip involves the displacement of formerly adjacent points, and these in practice can only be recognized where geological lines make piercing points with the fault surfaces (Crowell, 1959; 1962). For this reason, displaced shorelines, facies-change lines, isopachous lines, are especially useful. At a smaller scale so are trains of sedimentary debris carried downstream from distinct and recognizable source terranes; several of these are now known to be greatly offset. The geometry of separation, on the other hand, involves the displacement of surfaces. These surfaces make traces with the fault surfaces, and at many places, the slip vector has been oriented nearly parallel to this trace. For example, it is the vertical separa-

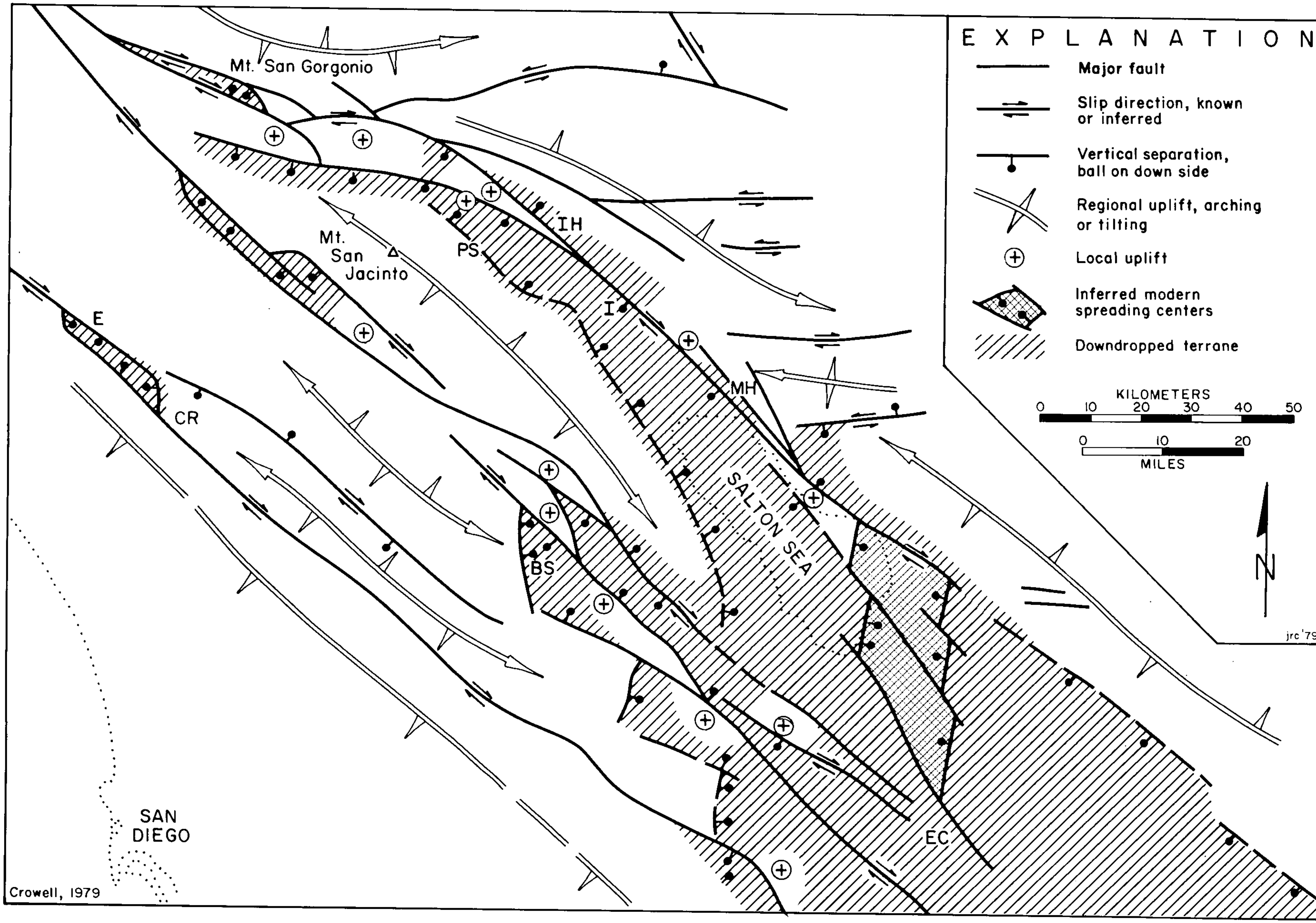


Fig. 2. Tectonic diagram of the Salton Trough and central Peninsular region. We use the term "porpoise structure" informally to designate locally uplifted or uparched blocks that alternate with downdropped or downsagged blocks between braided fault strands, such as along the San Jacinto fault zone NE and E of Borrego Springs (BS). CR, E, Lake Elsinore; PS, Palm Springs; IH, Indio Hills; I, Indio; MH, Mecca Hills; EC, El Centro.

tion of the topographic surface that we first observe when looking at a fresh fault scarp. It is also the vertical separation depicted in a cross section showing the "displacement" of a bed or contact, but this view has no _a priori_ relationship to the actual movement of one block with respect to the other. Strike-slip faults may cut through horizontal beds and displace them significantly without showing any vertical separation at all! It may be for this reason that some faults are considered as having died out when in reality they are as healthy as ever but have slip vectors that are parallel to the traces of the reference marker against them. Think again of ice floes moving laterally in a river or a current. Their surfaces stand at the same level even though differential movement between them is great. For crustal blocks, only if we find displaced lines and piercing points are we completely satisfied that major strike slip has occurred, and then only if we are certain of the correlations. Vertical contacts in basement terrane are also useful and tantamount to slip if we are dealing with a strike-slip fault.

Vertical separations are also variable along the trend of major strike-slip faults, and can be first high on one side and then high on the other. This can come about in at least two very different ways. If the terrane includes reference features that were previously deformed, these may be offset laterally so that a reversal in the sense of vertical separation results. Or, alternate stretching and squeezing of a crustal block along the strike of a major strike-slip fault during movement can bring about a similar geometry. In strike-slip country, faults with reversals in the sense of vertical separation are not necessarily scissors faults (that is, faults where the slip vectors have gone through a null point and increase in magnitude away from this point in both directions). More likely we are dealing with a major strike-slip fault with flexible walls, or with the lateral offset of a previously deformed terrane. If we are dealing as well with a branching or braided fault zone, vertical separations between the fault slices can alternately rise and fall.

SOME UNSOLVED PROBLEMS

Several major tectonic problems in western North America still await solution and involve knowledge of the geology at the Salton Trough-San Andreas juncture. Among these are an understanding of the reason for the Transverse Ranges and their origin, the source and history of the Salinian block, and whether or not there is a proto-San Andreas fault in southeastern California. Early Tertiary and older tectonic features such as the Vincent-Orocopia-Chocolate Mountain thrust system are still enigmatic. And so are satisfactory explanations for the sources of some conglomeratic units. Especially in need of appraisal is the role of tectonic rotations as shown by paleomagnetic data (Kamerling and Luyendyk, 1979; Luyendyk, Kamerling, and Terres, in press).

The Transverse Ranges make a distinct angle with the predominating northwest-southeast trend of the Coast Ranges and Peninsular Ranges, and are rising sharply today. The mountains form an imposing range with an east-west trend north of the Los Angeles Plain, and toward the east can be followed out into the Mojave Desert Province where they fade away. Rock units within the Transverse Ranges have been moved about, in large part before the range existed topographically. We must therefore distinguish between the fundamental structure of the Transverse Ranges and the topography today. The origin and history of the series of faults bordering the Transverse Ranges west of San Bernardino are also still unknown. In fact, some basement rock types within the San Gabriel Mountains are quite different in age and type from those within the Perris Block so that the Sierra Madre-Cucamonga fault system is especially significant.

The possible existence of a proto-San Andreas fault in southeastern California active during early Cenozoic time has been a subject of discussion for several years (Crowell, 1973, 1975a; Haxel and Dillon, 1978; Nilsen, 1978). Such a fault seems at first to be required in order to reconcile and to extend tectonic interpretations from central and northern California on southeastward into the Salton Trough. North of the Transverse Ranges, basement rock types within the Salinian Block (Pacific plate) are interpreted as having been offset about 600 km from their correlatives on the North American side of the San Andreas fault (Hill and Dibblee, 1953; Ross, 1973). In addition, Paleocene conglomerates near Point Arena in northern California are considered as having been derived from a basement source within the Transverse Ranges east of the fault zone and later displaced by right slip of about 600 km (Wentworth, 1968; Ross, 1973). A proto-San Andreas fault has therefore been advocated north of the Transverse Ranges (i.e., Nilsen and Clarke, 1975; Nilsen, 1978), but its simple extension to the southeast has not been recognized.

Basement rocks in southern California, on the other hand, are displaced only about 300 km (Crowell, 1960, 1962, 1975a, 1979; Ehlig and Ehlert, 1972), and displaced in Late Cenozoic time only. Moreover, this magnitude and timing is matched in central California, where displaced facies indicate about 300 km of slip since Late Miocene time (Hall, 1960; Addicott, 1968; Huffman, 1972). At least three hypotheses now find advocates to explain these tectonic relations, that is, two states (earliest Cenozoic and Late Cenozoic) of displacement north of the Transverse Ranges totaling 600 km of right slip, and only one (Late Cenozoic) to the southeast with 300 km of slip: (1) the proto-San Andreas fault does not exist either north or south of the Transverse Ranges, and displacement can all be accomodated by splintering and shifting of blocks beginning in Miocene time (Johnson and Normark, 1974; Graham, 1978; Crowell, 1979); (2) the proto-San Andreas is represented southeast of the Big Bend by the Vincent thrust system (Haxel and Dillon, 1978). According to this hypothesis, a long and narrow back-arc basin trended east-southeastward across southern California in which sediments and volcanic rocks accumulated, later to form the Pelona Schist. This basin was then closed obliquely to form the Vincent thrust, with a displacement component to account for the 300 km; and (3) a plate-tectonic scheme involving a transform to the west along the southern margin of the Transverse Ranges so that the first-stage San Andreas lay somewhere in the California offshore (Campbell and Yerkes, 1976). The resolution of the still unsolved problem of the "proto-San Andreas fault" must involve evidence garnered in the Salton Trough and adjacent tectonic provinces.

This discussion raises the question of the origin and history of the Salinian Block, the long terrane underlain by sialic rocks west of the San Andreas fault and north of the Transverse Ranges. Its original site is still unknown (Ross, 1978; Mattinson, 1978). It may have come from a region several hundred kilometers to the south and perhaps from east of the Peninsular Ranges.

This guidebook touches on the problem of the structure of the Salton Basin at depth (Keller, Chap. 6, this volume; Crowell and Baca, Chap. 10, this volume). Wells drilled for water, geothermal heat, and unsuccessfully for oil or gas have yielded intriguing insights to the stratigraphic and metamorphic processes at depth. Deep reflection seismic study of Salton Trough will yield data on the configuration of the Salton Trough-San Andreas juncture more completely. Seismic refraction studies now underway by the U.S. Geological Survey (Keller, Chap. 6, this volume) reveal a hazy glimpse of the deep structure of the basin. So now we anticipate eagerly the results of deep drilling as proposed by the Continental Drilling Program, in this, the most accessible and best-known juncture between divergent and transform plate boundary on Earth.

Another problem involves sorting out the relations between the Salton Trough region and basin-range tectonics.

Physiographically today the region is part of the Basin and Range Province but the westward extent of basin-range structure and its antiquity is still unclear. The Anza Formation in the western foothills of Imperial Valley of largely Middle Miocene age was apparently deposited in a basin-range regime. Within the Orocopia and Chocolate Mountains, basin-range faulting probably commenced in Oligocene time (Crowe, 1978), and a westward part is now offset to the north-central Transverse Ranges on the San Andreas fault system (Crowell, 1962; Bohannon, 1975). The relationship of this structure, however, to that still farther west, and a plate-tectonic explanation has not yet been worked out. Paleomagnetic data, however, indicate marked rotations of blocks within the region (Kamerling and Luyendyk, 1979), but a satisfactory regional synthsis remains elusive.

Associated with the problem of the extent of basin-range tectonics is the relation of the proto-Gulf of California to these structures. The proto-Gulf occupied the Salton Trough region between about 10 and 5 m.y. ago as shown by remnants of both marine and nonmarine strata (Karig and Jensky, 1972; Crowell and Baca, Chap. 10, this volume), and an arm extended northeastward well into the Basin and Range Province (Metzger, 1968; Blair, 1978).

Although we are emphasizing here Late Cenozoic tectonics, older tectonic features require research as well. Paramount among these is the huge Chocolate Mountain thrust system that is exposed at places east of the Salton Trough, and its relation to the Orocopia and Vincent thrusts farther north (Ehlig, 1968; Crowell, 1974c, 1975a; Haxel and Dillon, 1978). West of the Salton Trough is the Santa Rosa mylonite zone (Theodore, 1966, 1970; Sharp, 1967, 1979), a major movement zone of about the same age (Late Mesozoic?). In addition, the distribution of Precambrian rocks and their possible offset on a major left-slip system in pre-batholithic times pose intriguing problems (Silver and Anderson, 1974). On our excursion we will point out some of these older tectonic features and speculate on their significance.

SUMMARY

Probably nowhere on Earth is there a better place to study the joining of a divergent plate boundary with a major transform system than in the Salton Trough and its environs. The region is accessible and well exposed, especially in the desert, and has been the site of geologic and geophysical investigations for many years. Continued study of the region purports to tell us much concerning the tectonic details at such a juncture which, in turn, will embellish our understanding of plate-tectonic concepts. We look forward to showing you some of the highlights on our excursion.

Chapter 2

PLATE TECTONIC FRAMEWORK OF THE SAN ANDREAS-SALTON TROUGH JUNCTURE

by

Richard Terres and John C. Crowell

ABSTRACT

During Early Cenozoic time, the Kula plate on the west moved northward along a transform boundary relative to the North American plate. By Oligocene time the Kula-North American plate transform boundary was replaced by the Farallon-North American plate convergent boundary. Between 38 and 29 m.y. ago the Pacific plate first touched the North American plate near the present latitude of the Mexico-California border. A transform boundary was created along with a transform-transform-trench (FFT)triple junction on the northwest, and a transform-ridge-trench (FRT) triple junction on the southeast. From 29 m.y. ago to the present, the FFT triple junction moved northward to the Cape Mendocino area and the FRT triple junction moved southward to the mouth of the Gulf of California. During these triple-junction movements calc-alkaline volcanism ceased, bimodal volcanism commenced, and many basins and local uplifts formed. Both right-lateral faulting and conjugate left-lateral faulting ensued along the San Andreas transform system, and basin and range extension took place to the east.

About 15 m.y. ago, a proto-Gulf of California formed, apparently by extension along north-trending faults. By 8 to 10 m.y. ago, the proto-Gulf was a discontinuous marine basin that extended from the tip of Baja California to the Arizona-Nevada border. The San Gabriel fault in the Transverse Ranges of southern California also developed at about the same time. By 4.5 m.y. ago, the spreading ridge at the mouth of the proto-Gulf had connected with the FFT triple junction near Cape Mendocino via en echelon northwest-trending faults in the Gulf of California. This boundary has absorbed the Pacific-North American relative plate motion of 5.5 cm/yr since then. In the Gulf, oblique transform motion created pull-apart spreading

centers. In California, the San Andreas fault system developed several splays and bent segments and has formed a broad transform belt. The complex transform system of the San Andreas meets the oblique rifting system of the Gulf of California to the south in the Salton Trough. The result is strong and variable tectonic activity and its attendant high mountains, deep basins, volcanism, rapid sedimentation, and active faulting.

INTRODUCTION

The Salton Trough forms a prominent depression between the Peninsular Ranges on the west and the ranges of the Colorado and Mojave Deserts on the east. North and west of the Salton Trough the Pacific lithospheric plate slides past the North American plate along several faults of the San Andreas fault system. To the southeast, however, marked by the Gulf of California, the Pacific plate is now pulling away obliquely from the North American plate along a series of transform faults accompanied by small spreading centers. The Salton Trough, Coachella Valey, and high ranges of the San Gorgônio Pass region lie in the transitional area between these two tectonic systems. The tectonic interaction of these areas has resulted in the variety of geologic and topographic features within the region.

The topographic effects of the present tectonic activity are quite conspicuous where today a transform plate boundary meets a divergent boundary. Regional studies disclose, however, that this area has been at or near the active margin of the North American plate for well over 150 m.y. In Cenozoic time alone, three different plates coming in from Pacific regions have profoundly influenced western North America (Atwater, 1970; Atwater and Molnar, 1973; Dickinson, 1979; Dickinson and Snyder, 1979). The sequence of these several plate-tectonic events and their geologic results are described briefly below.

EARLY CENOZOIC TO OLIGOCENE

During Early Cenozoic time a ridge-trench-transform (RTF) triple junction apparently moved northwestward along the boundary of the North American plate, but the orientation of the ridge and the rate of movement are uncertain (Atwater, 1970). With the passing of this triple junction, the transform boundary between the Kula and North American plates was replaced by a convergent boundary between the North American and Farallon plates (Fig. 3). In southeastern California, this transition

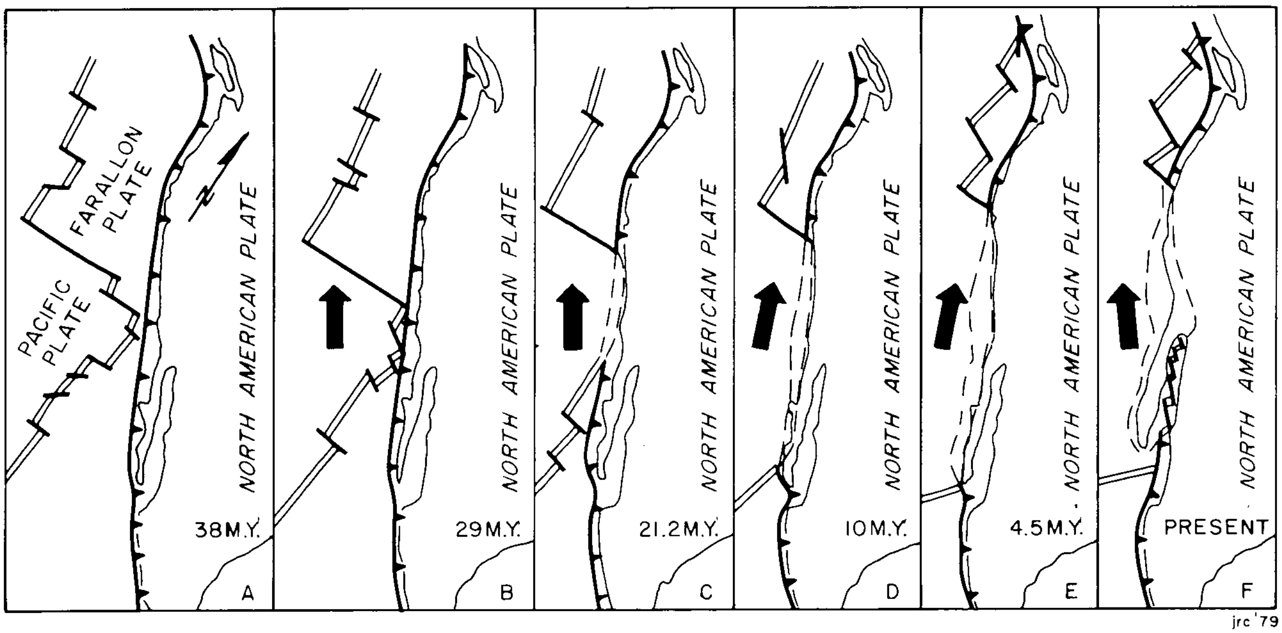


Fig. 3. Interpretive diagram showing interaction between the Farallon, Pacific, and North American lithospheric plates for six intervals of Tertiary time. The North American plate is considered fixed. The dashed line in diagrams C, D, E, and F outlines the transform region of basins interspersed with high-standing terrane. The present shoreline is shown on each map for reference although it did not have this configuration at the times of the diagrams. Transform plate boundaries are shown as single lines, divergent as double lines, and convergent as barbed. Redrawn from Beake and many others (1978, Fig. 2) after Atwater and Molnar (1973).

may be marked by the initiation of calc-alkaline volcanism around 35 m.y. (Crowe, Crowell, and Krummenacher, 1979). The location of the Kula-North American transform boundary prior to this may be reflected by the absence of early Cenozoic volcanism in southeastern California and in Mexico (McDowell and Keizer, 1977). In central California, as mentioned in Chapter 1 (Crowell and Sylvester, this volume) a proto-San Andreas fault may also have been active (Garfunkel, 1973; Nilsen and McKee, 1979).

By Oligocene time the Kula plate was far to the north and the Farallon plate was subducting obliquely beneath the western margin of the North American plate. This plate convergence caused widespread calc-alkaline volcanism (Christiansen and Lipman, 1972). A convex westward boundary evolved on the North American plate which had a typical trench, outer-arc ridge, fore-arc basin, and magmatic-arc configuration (Dickinson, 1976, 1979; Dickinson and Seely, 1979; Hamilton, 1979), but at places this geography was complicated by islands, basins, and continental embayments (Nilsen and McKee, 1979). As the Farallon plate was consumed during continued subduction, the Pacific-Farallon spreading ridge, marking the boundary with the Pacific plate, approached from the west.

OLIGOCENE TO MID-MIOCENE

Between 38 and 29 m.y. ago the Pacific plate first impinged upon the North American plate near the position of the present California-Mexico border (Atwater and Molnar, 1973). This plate collision created two triple junctions: a transform-transform-trench (FFT) triple junction which moved to the northwest, and a transform-ridge-trench (FRT) triple junction which moved to the southeast. These two triple junctions acted to replace an arcuate subduction zone by a straight transform system. Dickinson and Snyder (1979) noted that geometric considerations should result in making these unstable triple junctions. Therefore, plate-margin fragmentation, local crustal attenuation (basin formation and volcanism), and contraction (uplift) took place to achieve stability. The belt of subduction-related magmatism moved northward with time as the FFT triple junction migrated. In addition, the inception of basin and range block-faulting and related volcanism to the east may also have followed this triple junction (Christiansen and Lipman, 1972). Calc-alkaline volcanism related to the subduction of the Farallon plate continued until 22 m.y. ago (Crowe, Crowell, and Krummenacher, 1979). Accompanying this activity was extension on north- and northwest-trending faults (Crowe, 1978). Several fault-controlled basins formed west of the main volcanic terrane (Bohannon, 1975).

The faults which bound these Late Oligocene-Early Miocene basins presently strike approximately east-west, but paleomagnetic data raise the hypothesis that they have been rotated from an original north-south trend (Kamerling and Luyendyk, 1979) and were part of the larger scheme of crustal fragmentation, attenuation, volcanism and faulting which formed the southern California borderland and adjoining regions. Dickinson and Snyder (1979), Campbell and Yerkes (1976), and Blake and others (1978) attribute this activity to the southward movement of the FRT triple junction. Luyendyk, Kamerling and Terres (in press) relate these Middle Miocene features to simple-shear deformation and accompanying rotations between the Pacific and North American plates.

While the Farallon plate was subducting beneath Mexico, a broad calc-alkaline rhyolite plateau formed in Sonora and adjacent regions (McDowell and Keizer, 1977). In addition, as the FRT triple junction proceeded southward from the Transverse Ranges area, a narrow arc of andesite volcanoes developed just east of the present eastern shoreline of Baja California (Wilson, 1955; Gastil and Krummenacher, 1977). By 15 m.y. ago the FRT triple junction had moved south to the area of the Vizcaino Peninsula (Atwater and Molnar, 1973), and the calc-alkaline volcanic activity waned.

Basin and range extensional faulting also may have followed the FRT triple junction southward (Christiansen and Lipman, 1972). The inception of this normal faulting in the Chocolate Mountains east of the Salton Trough was around 32 to 26 m.y. ago (Crowe, 1978). At the latitude where the sedimentary rocks on the eastern margin of the Salton Trough were deposited (about 350 km south of the Chocolate Mountains) faulting began about 15 m.y. ago (McDowell and Keizer, 1977). The Anza Formation, exposed at the western margin of Imperial Valley, was apparently laid down in a basin-range setting in largely Middle Miocene time, and perhaps in Late Miocene time.

MIDDLE AND LATE MIOCENE

From 15 to 8 m.y. ago, the FRT triple junction moved to near the tip of the present Baja California (Atwater and Molnar, 1973) (Fig. 3). Almost all of the subduction zone was replaced by a transform boundary, causing the activity of the volcanic arc in Mexico to cease (Karig and Jensky, 1972). Following the end of volcanism, the arc was fragmented by extension along north- to northeast-trending normal faults (Wilson, 1955; King, 1969). Beginning 14 m.y. ago, this faulting was accompanied by the widespread eruption of a bimodal suite of volcanic rocks (rhyolite-basalt) (Gastil, Krummenacher, and Minch, 1979).

As extension proceeded, a proto-Gulf of California formed (Karig and Jensky, 1972; Moore, 1973), a gulf tectonically quite different in origin from the present gulf. Conglomerates exposed southwest of the Salton Sea (the Split Mountain Formation) indicate that a basin was forming in the northern proto-Gulf region in Late Miocene time (Crowell and Baca, Chap. 10, this volume). Microfauna collected from wells along coastal Sonora, Mexico, also suggest local marine deposition of this age (Moore, 1973).

By 8 or 10 m.y. ago, the proto-Gulf stretched north of the present Lake Mead area on the Arizona-Nevada border as a series of narrow basins along a chain from 50 to 150 km wide (Moore, 1973; Ingle, 1973; Blair, 1978). The basins of the northern proto-Gulf were shallow, while those to the south were well over a kilometer deep wherein more than a kilometer of sediments were deposited (Moore, 1973). Beneath the sediments, the crust of the Proto-Gulf was highly injected with volcanic material so that it is now intermediate in composition between continental and oceanic (Phillips, 1964).

Volcanic activity accompanied the formation of the proto-Gulf. Rhyolite and dacite erupted in its immediate vicinity (Gastil and Krummenacher, 1977), including the Alverson volcanics, became interbedded with the coarse clastic units (Korsch, Chap. 9, this volume).

The attenuated blocks which formed the basins of the proto-Gulf were apparently bounded by north-trending faults, although the proto-Gulf trend was northwest. This arrangement suggests that the proto-Gulf formed as a coalescing series of en echelon north-trending basins, related to oblique subduction to the west in which the terrane was disrupted by an extension within the arc and behind the arc (Menard, 1978). As extension proceeded, marine basins opened up in the area of the arc, a tectonic setting that has been compared by Karig and Jensky (1972) to the present-day setting of volcano-tectonic rift zones which form behind trench-arc systems.

In southern and central California the tectonic setting was quite different from that in Mexico. Right-slip faulting related to the transform motion between the Pacific and North American plates was occurring. In the borderland several faults were the site of significant slip in Miocene time: the East Santa Cruz Basin fault (Howell and others, 1974), the Hosgri-San Gregorio fault (Graham and Dickinson, 1978), and perhaps the Newport-Inglewood fault (Yeats, 1973; Harding, 1973; Barrows, 1974). Inland to the east, the Rinconada fault was active (Dibblee, 1976), and the San Gabriel fault was just beginning movement about 10 m.y. ago (Crowell, 1979).

Several presently east-west trending left-lateral faults were also active. Major faults of this system include the Santa Ynez fault (Sylvester and Darrow, 1979) and the Malibu Coast fault (Truex, 1976). Several basins, such as the Los Angeles, Ventura, Santa Cruz, Santa Maria, and Catalina basins, formed in association with these faults and accumulated thick sequences of sediments (Crowell, 1974b; Blake and others, 1978). To the east, in the area which would eventually develop into the Salton Trough, continental clastic sediments were transported toward these basins across a widely exposed basement terrane (Ehlig, Ehlert, and Crowe, 1975; Sylvester and Smith, 1976).

The manner in which this complex transform boundary joined with the volcano-tectonic rift system in Mexico is not clear. In general, southern California was a broad transform zone which narrowed to the southeast, whereas Mexico was a broad basin-range rift zone which narrowed to the northwest and extended east of the California borderland.

LATEST MIOCENE TO EARLIEST PLIOCENE

About 8 or 10 m.y. ago the San Gabriel fault, an ancestral San Andreas fault, was born (Crowell, 1979). This northwest-trending fault cut through basement terrane, and from its birth to about 4 m.y. ago it acquired about 60 km of right slip (Crowell, 1979). The slip rate on the San Gabriel was therefore 1.25 cm/yr, a significant portion of the then 4 cm/yr relative slip rate between the Pacific and the North American plates (Atwater and Molnar, 1973).

While the San Gabriel fault was becoming an important member of the transform system, the spreading ridge of the FRT triple junction moved toward the tip of Baja California. A system of en echelon northwest-trending faults extending through the narrow proto-Gulf connected the spreading ridge with the San Andreas fault system in southern California (Moore, 1973, Fig. 4). By 4.5 m.y. ago, the ridge arrived at the mouth of the proto-Gulf (Atwater and Molnar, 1973).

To explain this tectonic arrangement, perhaps the San Gabriel-San Andreas fault system intersected the northern proto-Gulf in the Salton Trough region. The fault system broke into northwest-trending en echelon segments, each of which began and ended on the north-trending faults, and so propagated in a stair-step fashion along the proto-Gulf. These events may also explain the pattern of spreading centers and transforms along the Gulf. The northwest-trending echelon segments occupied the proto-Gulf, because this region may have been more highly faulted and probably weaker than bordering continental regions as a result of its previous history as a volcano-tectonic rift zone within and behind an arc system. As these events continued, the San Andreas-San Gabriel fault joined with the FRT triple junction far to the southeast. Moreover the proto-Gulf persisted, and marine and non-marine sedimentation occurred throughout this interval (Durham and Allison, 1960). At places, however, centers of accumulation changed and migrated, and in the southern proto-Gulf, the sea floor was uplifted, deformed, and eroded prior to 4.5 m.y. ago (Moore, 1973).

PLIOCENE TO RECENT

Baja California began rifting away from mainland Mexico about 4.5 m.y. ago as is shown by magnetic stripes at the mouth of the Gulf (Larson, Menard, and Smith, 1968; Moore and Buffington, 1968; Larson, 1972; Larson, Mudie, and Larson, 1972). Movement away from Mexico apparently was parallel to the northwest-trending en echelon faults in the proto-Gulf. Between each pair of northwest-trending transform segments a pull-apart spreading center developed between north-trending normal faults. Rifting proceeded at a rate of 6 cm/yr, so that today the Gulf of California has opened a total of 240 km (Larson, Menard, and Smith, 1968). We visualize that the attenuated crust of the pull-apart basins was injected by irregular mantle diapirs when rifting began. As spreading centers matured, the zone of mantle diapirism narrowed and became oriented at high angles to the transform fault trend, as shown by the bathymetry of the Gulf of California (Henyey and Bischoff, 1973; Bischoff and Henyey, 1974; Sharman, 1976).

Several characteristics of these spreading centers are typical of mid-ocean spreading centers in addition to the pattern of magnetic stripes at the mouth of the Gulf and their association with the East Pacific Rise (Larson, Menard, and Smith, 1968). Thatcher and Brune (1971) found that the Wagner Basin in the northern Gulf of California has earthquake swarms which are similar to those of mid-ocean ridges; a strong positive gravity anomaly is present along the center of the Gulf of California (Biehler, 1964; Keller, Chap. 6, this volume); tholeiitic volcanism has accompanied rifting (Batiza, 1978; Gastil, Krummenacher, and Minch, 1979); and the southern half of the Gulf has crust which is only 6 to 10 km thick (Phillips, 1964).

Other characteristics, however, differ from those of mid-ocean spreading centers. An average heat flow reading of 4.9 HFU in the central Gulf of California is less than the expected 6.0 HFU (Lawver, 1976). Seismicity associated with magmatic intrusion has been recorded off the inferred centers of spreading (Reichle, 1975). Seismic reflection profiles show abandoned spreading centers and blankets of sediment that are more uniform than would be expected if all spreading were outward from one center (Moore, 1973; Bischoff and Henyey, 1974). The transform-fault trends do not define a unique relative motion pole (Sharman, 1976). Although the bathymetry shows that these spreading centers occupy basins rather than ridges (Moore, 1973), this may be a consequence of basin size and high sedimentation rate (Sharman, 1976). Because of the similarities and dissimilarities between the Gulf of California spreading centers and typical mid-ocean ridges, some geologists refer to this region as a "leaky" transform margin (Elders and Biehler, 1975; Hill, 1977). The Gulf is probably still in transition from a newly rifted margin to a truly mid-ocean ridge-transform system.

At the time the Gulf of California began rifting and opening, the modern San Andreas fault tectonically bypassed the San Gabriel fault, thus becoming the major transform boundary between the Pacific and the North American plates (Crowell, 1979). Correlative basement terranes in the San Gabriel Mountains and the Orocopia Mountains indicate that about 240 km of displacement has occurred across the San Andreas fault beginning about 4 m.y. ago (Crowell, 1962). This fault alignment therefore has a slip rate of 6 cm/yr, the same as the Gulf of California opening rate. If, however, about 60 km of combined displacement of the San Jacinto and Elsinore faults are added during the same time interval, the total right slip is 300 km, giving a slip rate of about 8 cm/yr.

The San Andreas fault originally was straighter but now displays two significant bends: one in the San Gorgonio Pass region at the northwest end of Salton Trough and the other in the Tejon Pass region, northwest of Los Angeles. These bends inhibit the easy sliding of the Pacific plate past the North American plate. The San Jacinto fault may have been born in Late Pliocene time so that the Pacific plate could bypass the constraining bend in the San Gorgonio Pass region (Crowell, 1979), but the tectonic history of the "Big Bend" in the Tejon Pass region is still obscure. These two bends, since they constrain the relative plate motion, are the sites of local contractional tectonics and significant uplift. This process may account for the height of the San Gabriel and San Bernardino Mountains, and for the great elevation of Mount San Jacinto and Mt. San Gorgonio (Greyback).

To the southeast, however, the uplands flanking the Salton Trough are the result of thermal uplift due to the rising isotherms which preceded rifting (Elders and others, 1972). As rifting developed, the crust beneath the Salton Trough was stretched and attenuated and broken, resulting today in the deep and narrow valley. At the northwest these flanking uplands are apparently raised still higher by contraction across the San Gorgonio constraining bend.

THE PRESENT

The joining of the complex transform system in southern California to the transform-pull-apart system in the Gulf of California is obscured today beneath sediments in the Salton Trough and vicinity. Presumably the San Andreas, San Jacinto, and Elsinore faults each end at a pull-apart basin (Elders and others, 1972; Crowell, 1974b, 1975a). Both the Elsinore and the San Jacinto faults now disappear beneath alluvium near the head of the Gulf of California, and cannot be projected directly into any of the identified transform faults of the northern Gulf (Henyey and Bischoff, 1973). The San Andreas proper, on the other hand, apparently now ends in a developing pull-apart basin southeast of the Salton Sea (Hill, Mowinckel and Peake, 1975; Johnson and Hadley, 1976; Keller, Chap. 6, this volume).

The region of Salton Trough is in a transition zone where crustal rifting processes have conjoined with transform faulting to mold deep valleys surrounded by high mountains. The tectonic processes include active thrusting, extension, and horizontal and oblique slip, accompanied by active volcanism, high heat flow, and metamorphism in the developing rift itself. The mountains flanking this ever-widening valley have poured large volumes of clastic sediments into it, and gravity and seismic studies indicate that the Salton Trough is filled with over 6 km of sediments (Biehler, Kovach and Allen, 1964; Keller, Chap. 6, this volume). The terrane we cross on our excursion is therefore the consequence of tectonic and associated processes at depth operating vigorously today, and have followed on directly from the same processes operating just as vigorously back a few million years into Late Cenozoic time.

Chapter 3

LATE CENOZOIC FAULTS IN SOUTHEASTERN CALIFORNIA

by

John C. Crowell and Vincent Rex Ramirez

ABSTRACT

Faults of the present northwest-striking San Andreas system include the San Andreas fault zone proper, the San Jacinto, and the Elsinore. The San Andreas fault originated about 8 or 10 m.y. ago and has acquired a total right slip of about 320 km as shown by the offset of distinctive basement terranes and trains of Late Miocene conglomerates displaced from their source areas. The San Jacinto and Elsinore fault zones on the west side of Salton Trough are probably younger, and originated in Late Pliocene time in association with the opening of the present Gulf of California. Each of these right-slip faults is inferred to have a displacement of the order of 30 km.

Some N-S faults may have originated during the opening of the proto-Gulf of California along a volcano-tectonic rift zone. NNW-striking faults, such as the active Imperial and Brawley faults, may have been born as synthetic (R) shears owing to fundamental right simple shear between the Pacific and North American plates beneath sediments of the Salton Trough. Those faults with near E-W strike are considered to include those of pre-San Andreas origin and others that may have originated as antithetic (R') shears in a simple-shear system.

INTRODUCTION

Major faults in southeasternmost California include those that belong to the San Andreas system with a northwesterly trend, another set approximately west-northwesterly in strike and a third set that ranges in strike from NE to E. Those that we describe briefly here have been active during Late Cenozoic time and many are still active. Most originated in Late Miocene or younger times, but a few have followed older tectonic trends. Inasmuch as the region has been the site of major deformations as far back into time as we can trace a record, many of the major tectonic features are older than those dealt with here. Among these are the metamorphic movement zones associated with the Orocopia-Chocolate Mountain thrust system and the Santa Rosa mylonite belt. The emphasis here, however, is upon the relationships of those geologic structures that are involved in the tectonic juncture between the Gulf of California divergent plate boundary on the SE and the San Andreas transform system to the NW.

The San Andreas fault system refers to the group of high-angle subparallel fault zones with a northwesterly strike. Many of these faults and fault zones are active and have demonstrable right slip or low-angle oblique slip. Some members of the system such as those within the complex San Gorgonio Pass region are now bent and deformed, and in a few cases have probably changed their slip orientations through time as these deformations continued. Although we are concerned here mainly with the principal strands of the San Andreas system the region is coursed by many small faults of the same strike and character; these probably have similar orientations of slip and similar tectonic histories.

Major fault zones within the San Andreas system are complex, and include faults with many orientations of both attitude and slip. For example, we shall observe details within such a fault zone on our traverse through Painted Canyon where "palm-tree structure" and associated thrust faults and tight folds are on display (Sylvester and Smith, Chap. 12, this volume). At other places the fault zone itself is up to several kilometers wide, and in the Borrego Desert braided fault zones branch or splay into distinctly different zones separating crustal blocks. It is along such zones that we colloquially apply the concept of "porpoise structure." Here and elsewhere, strands, and especially strands that are active, have an en echelon arrangement within the zone as a whole.

Fault zones with easterly and northeasterly strikes are especially significant along the northeastern margin of the Salton Trough, in the Little San Bernardino, Orocopia and Chocolate Mountain chain, but are locally conspicuous as well in many other parts of the region. Some of the faults are no doubt conjugate fractures that originated synchronously with those of the San Andreas trend. Others, however, are interpreted as older faults, probably formed during Oligocene or Early Miocene time and have then been displaced for many tens of kilometers by later major movements on faults of the San Andreas system. The Salton Creek fault, for example, may be a displaced segment of the Big Pine fault in the northern Transverse Ranges and now offset about 320 km. Whether it originated as a conjugate fault to the offsetting San Andreas set of faults is therefore obscure. Moreover, during these displacements of many tens of kilometers, tectonic blocks are postulated to have been rotated, judging from paleomagnetic data (Kamerling and Luyendyk, 1979; Luyendyk, Kamerling and Terres, in press). Fault sets with displacements less than a few kilometers, as in the eastern Orocopia Mountains, form convincing conjugate sets. In addition, joints with a similar conjugate arrangement show up clearly on aerial photographs in some of the arid regions, as in the Mecca and Indio Hills.

Faults and folds in many parts of the region, and especially within the Borrego Desert, Indio and Durmid Hills, have arrangements showing that they have originated through simple shear (Fig. 4). These are particularly well developed where thick alluvium of latest Cenozoic age lies upon previously deformed older rocks, including basement. Anticlines are in en echelon arrangement with strands of the San Andreas fault system, so that their axial crests are sidestepped to the right. Extension fractures, resulting in grabens and horsts in surficial deposits, strike nearly normal to the crestal lines of these folds. Vertical conjugate fault systems with both synthetic and antithetic orientations are present. In fact, even with a decrease of scale, and in looking at larger and larger areas, the same simple-shear scheme is perhaps recognizable. For example, some of the east-striking faults of the Chocolate and Little San Bernardino Mountains may be rotated antithetic faults.

The Hidden Spring, Imperial, and Brawley faults, as well as many within the Indio, Mecca and Durmid Hills, make up a third group of faults discussed here that may originate through simple shear. Perhaps the margins of pull-apart basins, now forming beneath the Salton Trough, and the orientation of spreading centers within them are in part controlled by the extension direction of the simple-shear arrangement. On the

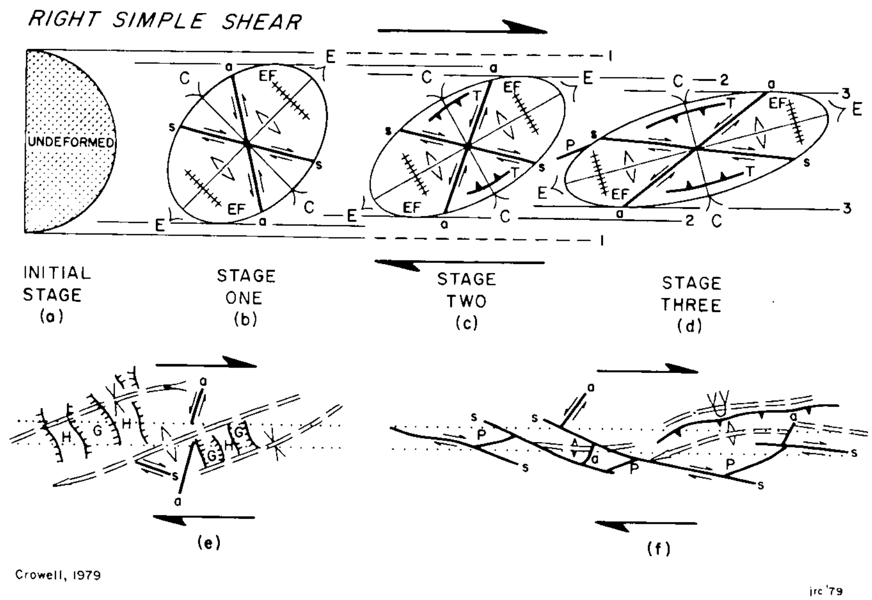


Fig. 4. Diagram showing the arrangement of structures in map view where strata lying above a throughgoing basement shear zone are deformed by right simple shear. An undeformed circle initially is deformed through three stages in the upper part of the figure. By Stage One the deformation is sufficient so that the circle is deformed into an ellipse and a conjugate fault system with an angle of about 62^{o} between antithetic (a) and synthetic (b) faults has formed as the result of contraction (C) directed normal to a growing fold whose crest is stretched in the direction of extension (E). Extension fractures (EF), resulting in irregular horsts and graben with strikes nearly normal to the fold crestal line, begin to develop at this stage as well. As deformation continues into Stage Two and Stage Three, the orientation of the fold crestal lines makes an increasingly smaller angle with the shear direction, and the angle between the antithetic and synthetic faults increases. The strikes of synthetic faults rotate closer and closer to the strike of the throughgoing shear, and at a stage somewhere between Stages Two and Three, faults along P direction develop (P shears). The antithetic faults rotate as well, but into a position of blockage, and so many die out. As the fold tightens, thrust faults (T) with strikes parallel to the strikes of the axial surfaces of the folds begin to grow. Material balance factors need to be considered as well: note that the width of the deformed zone as shown decreases from the width of the deformed zone as shown decreases from the width at 1 through that of 2 to 3. Diagram e shows a sketch map of a typical arrangement of folds, horsts, graben, and antithetic and synthetic faults. In a right-shear system the folds are aligned with an en echelon scheme, and step right. Diagram f shows a similar sketch map where synthetic faults are arranged in an en echelon pattern, and step to the left. The orientation and position of the basement shear at depth is shown by the parallel dotted lines.

other hand, Terres and Crowell (Chap. 2, this volume) infer that old faults that formed parallel to the margins of the proto-Gulf of California may have controlled the orientation of pull-apart basin margins as well as the en echelon scheme of spreading centers and transform faults with the present Gulf of California.

SAN ANDREAS FAULT ZONE

A belt of faults enters the Salton Trough at the northwest end of Coachella Valley consisting of the San Andreas proper, Mill Creek, Mission Creek, Banning, and Garnet Hill faults. On many maps the Mill Creek-Mission Creek fault is labelled the North Branch of the San Andreas and the San Andreas (S.S.) and Banning faults, the South Branch. Farther to the northwest, these branches join near the Cajon Pass region, whence they can be traced on northwestward through California to the Mendocine triple junction. To the southeast, the north and south branches converge as well, and can be traced as a more restricted zone to the vicinity of Niland, east of the Salton Sea. This belt of faults constitutes the main transform boundary between the Pacific and North American plates inasmuch as it is the belt along which the major displacement is documented (Crowell, 1960, 1962, 1979). From the viewpoint of present activity and straight alignment parallel to the motion directions of the two lithospheric plates, however, the San Jacinto fault zone might just as well have been named the San Andreas fault zone by early workers.

The tectonics of the San Gorgonio Pass region, including the history of displacements on this belt of faults where they pass through the region, has not yet been satisfactorily elucidated. Modern mapping at large scale in the very rugged terrane is still required before we can understand how the several branches mesh and how they formed. It is not yet known how the Pinto Mountain fault, coming in from the east, joins with the other faults and how it contributed to the mosaic (Allen, 1957; Proctor, 1968; Dibblee, 1973). The Banning fault in San Gorgonio Pass itself has 9 km of right slip upon it, judging from the displacement of late Pliocene or Pleistocene markers and at least 1600 m of dip separation (Allen, 1957). Displacements of older rocks along the fault may be considerably greater, however, in view of the contrast in basement rocks across it (Ehlig, 1977), but at the surface today it displays only thrust geometry. This is probably due in part to the oblique upward squeezing of the basement massifs north of the fault as the constraining bend in the tectonic scheme is reinforced. This same late deformation is also inferred to have bent and re-aligned the Mill Creek-Mission Creek system and perhaps to have originated other faults in this tectonic knot. In general, the fault pattern looks like a complex conjugate system formed as the result of pure shear at the constraining bend, but superposed upon a through-going simple shear pattern in the past.

East of San Gorgonio Pass both the Mission Creek and Banning faults are active as is shown by fault-formed landforms, groundwater barriers, and seismicity (Proctor, 1968; Richter and others, 1958). In the Indio and Mecca Hills Quaternary deposits are distinctly deformed at many places with an arrangement of structures indicating simple shear, in surficial deposits above a fundamental right-slip zone at depth (Fig. 4). Farther to the southeast similar structures are traceable through the Durmid Hills, and a few shallow graben have been identified in the alluvium east of Niland. Beyond this area, however, there is no compelling evidence that the San Andreas continues as an active fault, although a zone of faulting clearly extends at depth with a southeasterly trend along the margin of the Imperial Valley and into Mexico near Yuma (Olmstead and others, 1973). This fault zone, including the Sand Hills and the Algodones faults, is interpreted here as an inactive extension of the San Andreas, but one with unknown right slip upon it older than the opening of the Gulf of California 4 m.y. ago. The San Andreas system apparently does not now extend into the North American plate beyond the spreading centers within the rifting Salton Trough (Crowell, 1974a, in press). This interpretation is supported by the pattern of seismicity, subsidence, geothermal metamorphism and recent volcanism beneath the Imperial Valley (Elders and others, 1972; Hill, Mowinckel and Peake, 1975; Johnson and Hadley, 1976). Here at depth lies a pull-apart basin associated with spreading centers involved with the movement of the Peninsular Ranges of the Pacific plate as it slides northwestward away from the North American plate along this relatively divergent plate boundary. The active San Andreas transform ends near Niland and the plate boundary farther south is marked by the series of en echelon spreading centers within the Gulf of California.

The total slip recognized on the San Andreas fault zone is about 320 km, including displacement on the San Gabriel fault within the central Transverse Ranges (Crowell, 1960, 1962, 1975a 1979; Ehlig and Ehlert, 1972; Ehlig, Ehlert and Crowe, 1975). All rocks older than Late Miocene appear to be displaced the same maximum amount. Distinctive rock types among clasts within the Mint Canyon and Caliente Formations, now found west of the San Andreas in the north-central Transverse Ranges, were derived from the northern Chocolate Mountains and vicinity (Ehlig, Ehlert, and Crowe, 1975). These beds are probably between 10 and 12 m.y. old (Woodburne, 1975) so the displacement took place some time thereafter.

The Coachella Conglomerate (Peterson, 1975) exposed in the eastern part of the San Gorgonio Pass region between the north and south branches of the San Andreas fault consists of about 1500 m of fanglomerate derived from a source area to the north, now truncated and offset by the Mission Creek-Northern Branch. The fanglomerate contains distinctive boulders of porphyritic quartz monzonite and magnetite. A suitable terrane has only been recognized in the southernmost Chocolate Mountains and vicinity, an offset distance of about 215 km (Peterson, 1975), but since the Coachella Conglomerate is present between the two fault branches, this correlation, if sound, may not document the total slip. Near the base of this wedge of fanglomerate are andesite flows and breccias, dated at 10 ± 1.2 m.y. by K-Ar methods (Peterson, 1975). Faulting therefore started at this time or shortly thereafter. An age of about 10 or 8 m.y. ago for inception of the San Gabriel fault in the central Transverse Ranges is indicated by the age of the Violin Breccia (Crowell, 1979, in press). Taken together these data indicate that the San Andreas fault in southern California originated between 10 and 8 m.y. ago; it is distinctly older than the opening of the Gulf of California as shown by magnetic-anamoly stripes at the mouth of the Gulf (Larson, Menard, and Smith, 1968; Larson, 1972).

SAN JACINTO FAULT ZONE

A major strand of the San Andreas system, the San Jacinto fault zone, extends southeastward with a remarkably straight course from the Cajon Pass region to the Borrego Desert and beyond as a series of branches into the Salton Trough. The fault zone includes several faults, such as the Casa Loma, Coyote Creek, Buck Ridge, Clark Valley, San Felipe Hills, Superstition Hills, and Superstition Mountain faults. The zone is active as shown by continued seismicity (Allen and Nordquist, 1972; Hill, Mowinckel, and Peake, 1975), and several earthquakes with magnitudes somewhere between 6 and 7 have taken place since 1912 (Allen and Nordquist, 1972). The Borrego Mountain earthquake of April 9, 1968, with a magnitude of 6.4 is notable because it led to one of the most detailed studies of earthquake effects up to that time (Sharp and others, 1972).

At places along the fault excavations show that the faults cut recent alluvium (Proctor, 1962; Sharp and others, 1972; Hart, 1979) and serious ground breakage has locally required reconstruction and relocation of buildings (for example, Allen, 1971).

The total right slip on the San Jacinto fault zone is probably about 30 km as shown by the map separation of high-angle basement rock contacts (Sharp, 1967; Bartholomew, 1970). Vertical separations along it are striking and locally exceed 3 km with the structurally higher block on either side. Where the fault zone splays upon entering the Borrego Desert from the northwest, high-standing blocks within the zone are flanked by alluviated depressions as where Coyote Mountain stands between Borrego Valley and Clark Valley. This pattern suggests that some blocks are squeezed upward and others depressed in accordance with the principles of fault convergence and divergence along a branching strike-slip fault zone (Crowell, 1974b), constituting what we here call informally "porpoise structure" (Crowell and Sylvester, Chap. 1, this volume). Several deep depressions, such as the San Jacinto Valley between the Casa Loma and the main San Jacinto fault, appear to be pull-apart basins where the crust has stretched and sagged within a right-slip regime. The length of this long basin parallel to the fault-zone trend is nearly 40 km, which, under the assumption that it has indeed formed as a long and narrow pull-apart, would give maximum slip of this magnitude, but the actual right slip is probably less in view of expected attenuation at the ends.

The antiquity of the San Jacinto fault zone is not known with certainty. Along the northwestern reaches of the fault zone, the oldest sedimentary strata associated with the tectonics of the zone, such as the Mt. Eden, San Timoteo and Bautista Formations, are Plio-Pleistocene in age based on sparse vertebrate and plant remains (Morton and Gray, 1971, p. 72), or younger than 5 m.y. ago. Until further data are available it seems reasonable to consider the San Jacinto fault as no older than these strata, or about mid-Pliocene. The fault may be younger (i.e., Latest Pliocene or Early Pleistocene), however, inasmuch as the Upper Pleistocene Ocotillo Conglomerate is offset laterally about 16 km as shown by the displacement of inferred source areas from derived detritus (Bartholomew, 1970, p. 3164) and assuming that its rate of movement has been nearly constant throughout its lifetime.

THE ELSINORE FAULT ZONE

The northern Peninsular Ranges are transected by the Elsinore fault zone. At its NW end it strikes SW out of the conjuncture of the Whittier-Chino faults. The Elsinore fault zone is made up of a right-stepped series of straight reaches into the eastern Peninsular Ranges where it forms the straight margin of the Laguna Salada and Sierra de los Cucapahs in Mexico. In common with the San Jacinto fault zone, the Elsinore also is more splayed at its southeast end as it approaches the divergent plate boundary. The relationship of the Elsinore fault zone to the Whittier and Chino faults on the northwest and whether these two faults have truly been parts of the Elsinore through time are problems still being studied by California geologists. And so are the relations of these two faults in turn to the Transverse Ranges and the history of the Los Angeles basin.

The magnitude of right slip on the northern part of the Elsinore fault is perhaps as much as 40 km as shown by offset facies-change and pinch-out lines in the Paleocene sequence (Lamar, 1961; Sage, 1973) (Fig.5). As yet, however, this slip has not been confirmed by the discovery of offset features within the widely exposed basement terrane through the central Peninsular Ranges, although there are contrasts in basement rock type across the fault zone at many places. Vertical separations are variable along the fault zone; they are as much as 3 km at Lake Elsinore (structurally high terrane on the southwest) and flanking Coyote Mountain near the Mexican border (high in the northeast). The Sierra de los Cucapahs also stand high on the northeast with respect to the fault zone along its base bordering Laguna Salada. Knowledge of the age of the fault zone is poor, largely because of the lack of Late Cenozoic sedimentary rocks along its course. In view of its tectonic similarities with the San Jacinto fault zone, it is here also considered as probably of Plio-Pleistocene age. It is active as shown by fault landforms along its course (Weber, 1975) and by low-level earthquake activity (Langenkamp and Combs, 1974).

NNW-STRIKING FAULTS

Two groups of faults within the region strike north-northwesterly: those beneath Imperial Valley, and splays from major faults of the San Andreas zone. The Brawley and Imperial faults,

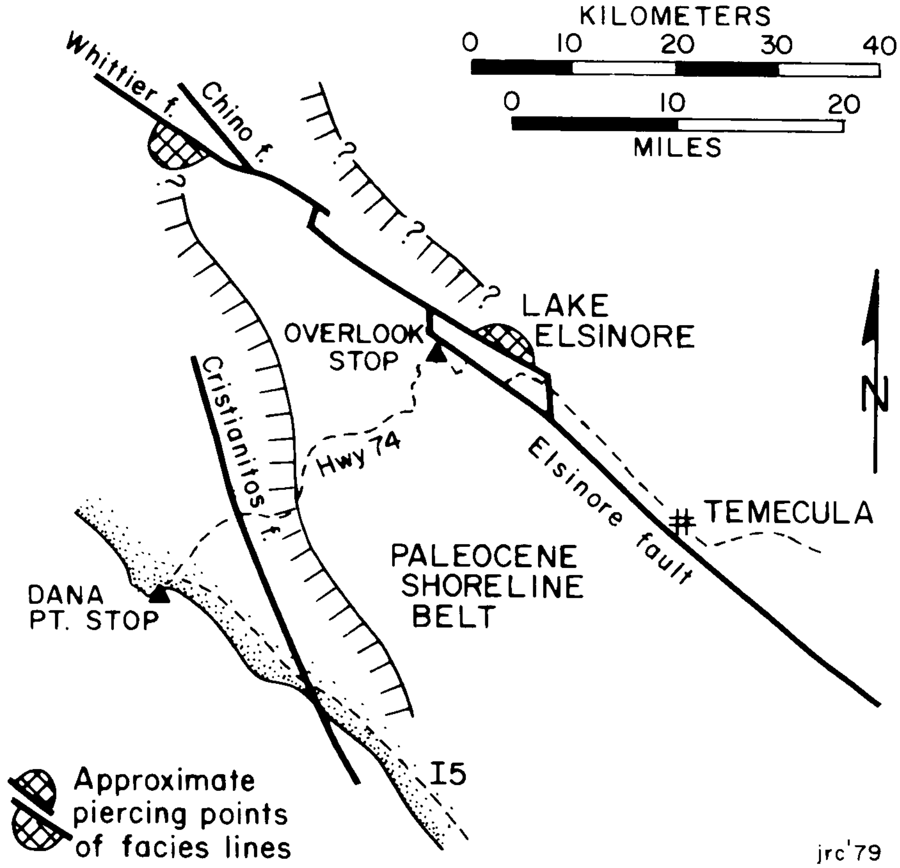


Fig. 5. Sketch map showing geometry of probable right slip on Elsinore fault zones. Offset geological lines in Paleocene beds include facies-change lines, pinch-out line and isopachous lines. Refer to text for explanation. Base from Jennings, 1977.

now active, are subparallel and bound Mesquite Lake, a subsiding depression on the alluvial flats of Imperial Valley. Displacement on these faults, with others, (such as the Calipatria) is accompanied by earthquake swarms (Keller, Chap. 5, this volume) and is interpreted as being associated with underlying small spreading centers (Lomnitz and others, 1970; Elders and others, 1972; Sharp, 1976; Trifunac, 1972; Johnson and Hadley, 1976; Hill, Mowinckel and Peake, 1975; Hill, 1977; Keller, Chap. 6, this volume). The strike of these faults makes an angle of about 25^{o} with that of the San Jacinto and San Andreas faults. In addition, several faults branch off from the San Andreas fault zone with NNW strikes such as the Hidden Springs and Indio Hills faults and others that are unnamed. Moreover, the northern branch of the San Andreas (Mission Creek fault) meets the southern branch with a similar angle in the center of the Indio Hills. Both groups of faults follow the synthetic (R shear) direction of a simple shear system where thick sedimentary cover overlies a deep basement right-slip zone (Riedel, 1929; Wilcox, Harding and Seely, 1973) (Fig. 4).

The down-dropped scarps in the alluvium between the Brawley and Imperial faults (Sharp, 1976) make an angle of at least 30^{o} with the inferred north-northwesterly trends of the faults at depth. These relations suggest that the scarps are forming normal to the extension direction of the simple-shear deformation ellipse which is oriented to the simple-shear couple (Fig. 4). A small pull-apart is probably forming here (see also Keller, Chap. 6, this volume) with a shape and intrusion pattern at depth controlled by simple shear along the plate margins.

Some of the faults with a near N-S strike, such as the one W of Split Mountain Gorge, may be members of the set formed during the opening of the proto-Gulf of California (Terres and Crowell, Chap. 2, this volume). In fact, the pull-apart margins of some of the growing spreading centers now beneath the Gulf of California may be determined by these proto-Gulf directions.

E-STRIKING FAULTS

Several conspicuous faults that are active, recently active, or presumed dead, extend eastward from the San Andreas fault zone. From north to south the principal ones are: Pinto Mountain, Blue Cut, Porcupine Wash, Chiriaco, Salton Creek, Mammoth Wash and Black Eagle Mine faults along with several that have not been named. In approaching the San Andreas most of these vertical faults curve gently southwestward. Basement rocks are severely sheared along the faults and at places patches of Quaternary alluvium are tilted and downdropped, indicating Late Quaternary movement. Left slip is shown on some by offset of high-angle basement contacts, but high topographic relief locally suggests that the dip-slip component is considerable.

Along the central stretch of the Pinto Mountain fault, near-vertical basement contacts are offset between 12 and 16 km laterally (Dibblee, 1975). The W end of this fault curves southward and branches as it meets the San Andreas in a pattern suggesting conjugate fractures formed under pure shear. The Blue Cut fault lacks the recent geomorphic expression of the central Pinto Mountain fault, but it has near-vertical Pleistocene (?) gravels in slices along it. Offset basement contacts show an increase in separation from about 3 km on the W to 8 km on the E (Hope, 1966). On the E both of these faults merge or are truncated by northwesterly striking fault zones.

The Chiriaco fault lies beneath the unfaulted alluvium of Hayfield Valley and is not exposed; but separations of basement contacts across the valley show a left separation of about 10 km (Powell, 1975). The Salton Creek fault has an E-W strike along Salton Creek Wash where it is marked by a series of volcanic knobs interpreted as plugs that have come up along the fault in Miocene time (Crowe, Crowell and Krummenacher, 1979). K-Ar dates show that the domes were emplaced between 27 and 33 m.y. ago, so the fault was present at that time and was thereafter overlapped by a capping volcanic sequence 13 to 22 m.y. old. It is a major Oligo-Miocene fault, and marks the northern boundary of the large volcanic field in the northern Chocolate Mountains and truncates NW-trending dike swarms and associated plutonic rocks. The Salton Creek fault is therefore older than the San Andreas system and it may be a displaced segment of major old faults in the central Transverse Ranges, such as the Big Pine fault about 320 km to the NW. The Clemens Well fault, a right-slip fault zone, either merges with the Salton Creek fault, or more likely truncates it at a small angle and then curves eastward from its northwesterly trend. Quaternary gravels are uplifted along it but recent alluvium is not cut; the Clemens Well fault is therefore inferred to have been active until very recently. In the southern Chocolate Mountains, the Mammoth Wash faults display left separations of about 8 km on steeply dipping basement contacts, and the Black Eagle Mine fault shows about 5 km (Dillon, 1975). Dip separations are here as elsewhere up to 1 km, but Plio-Pleistocene (?) conglomerates are not displaced.

These easterly trending faults may have at least three tectonic origins. First, some, such as the Salton Wash, are older than the San Andreas fault system and presumably have no relation to it; they have been truncated and displaced for many tens of kilometers by strands of the system and perhaps rotated. Second, some, such as the Pinto Mountain, may originate as parts of a conjugate system under pure shear as the San Gorgonio bend in the San Andreas system developed. Dibblee (1968) suggests that the Blue Cut and Chiriaco faults originated in this way, and then were carried southeastward away from the bend as displacement increased on the through-going San Andreas system. Support for this explanation comes from the observation that the faults appear to be older toward the southeast. Third, the faults have a strike that fits the antithetic trend with simple shear so that they may originate, rotate, and die out as right slip accumulates on the San Andreas system. Unfortunately, datable volcanic and sedimentary strata throughout the region of the faults, and either cut or not cut by them, are not widespread so that details of their tectonic histories cannot be worked out.

Chapter 4

NEOTECTONICS OF THE SALTON TROUGH

by

Thomas Rockwell and Arthur G. Sylvester

ABSTRACT

The Salton Trough is one of the most seismically active parts of California as indicated by frequency of felt and recorded earthquakes, geodetic measurements, tectonic geomorphology along mapped faults, and by offsets of radiometrically dated strata in trenches across faults. Besides earthquake swarms that occur frequently and typically in Imperial Valley and the northern Gulf of California, notable earthquake activity since habitation of the trough at the turn of the century includes the 1940 Imperial Valley earthquake (M 7.1 with up to 6.3 m of right-lateral offset at the International Boundary), the 1948 Desert Hot Springs earthquake (M 6.5), and the Borrego Mountain earthquake (M 6.4). Geodetic measurements show that the rate of shear strain across the trough is about 50 mm/yr. Scarps, offset stream courses, sags, shutter and pressure ridges and offset alluvial fans all show geological recency of fault movements, and locally, studies of these features show that displacements of up to 3 m take place in single events with return frequencies on the order of a few hundred years. Tilted, warped, folded and faulted Quaternary strata around the margins of the trough clearly attest to the intensity and duration of the neotectonic deformation.

INTRODUCTION

The Salton Trough region, characterized by its high level of seismicity, high heat flow, and dextral strain, has been the epicentral area for many large and numerous moderate to small earthquakes. Studies of these earthquakes, associated displacements, geodetic data and geomorphic features clearly show that shallow-crust deformation takes place as right slip on the major faults of the San Andreas system; additional pull-apart motion may also occur at spreading centers between en echelon segments of the main faults (Lomnitz and others, 1970, Elders and others, 1972; Crowell and Ramirez, Chap. 3, this volume).

The Imperial Valley has been one of the most seismically active areas in the western United States in recent years. The historic record of seismicity dates back to only about 1903, at which time people began to settle in the valley (Ulrich, 1941). Between 1903 and 1940, twenty moderate to large earthquakes occurred in the southern Imperial Valley principally along the Imperial, Superstition Hills, southern San Jacinto, and Brawley faults (Ulrich, 1941; Allen and others, 1965). Although the earthquakes caused considerable damage to the towns in the vicinity of those faults, most of their epicenters are not precisely known. Surface displacements were not documented with any of the earthquakes until the May 18, 1940, earthquakes which had up to 6.3 m of right slip associated with them (Ulrich, 1941; Trifunac and Brune, 1970; Sylvester, 1979). Since then, only a few moderate earthquakes have occurred on these faults, yet there has been an abundance of smaller events. In recent years with the increase in the number of seismographs in the area, the ability to detect and locate them has also increased (Allen and Whitcomb, 1978; Fuis, 1978; Hill, Mowinckel and Peake, 1975).

Geodetic triangulation data accumulated from 1941 to 1954 yielded dextral shear rates of 8 cm/yr over the entire Salton Trough region from the Chocolate Mountains on the east to the San Diego Mountains on the west (Whitten, 1956). More recent studies indicate that those data were contaminated by the 1940 (M 7.1) Imperial earthquake, and that the relative motion between the Pacific and North American plates in this region is 4.9 ± 1.5 cm/yr of which 2.5 ± 0.8 cm/yr is across the San Andreas fault, 1.7 ± 0.9 cm/yr is across the San Jacinto fault, 0.7 ± 0.9 cm/yr is across the Elsinore fault, and 4.6 ± 2.1 cm/yr is across the Imperial fault (Savage and others, 1979).

Savage and others integrate these data into a tectonic model for the Salton Trough proposed by Lomnitz and others (1970) in which the spreading rates of spreading centers decrease progressively to the north. That model requires that the sum of the slip on the San Andreas and San Jacinto faults must equal that on the Imperial fault, and the sum of slip on the Imperial and Elsinore faults must equal that on the southern San Jacinto fault. For comparison, the rate of deep slip on the San Andreas and San Jacinto faults (4.2 ± 1.2 cm/yr) is close to the deep slip rate on the Imperial fault (4.6 ± 2.1 cm/yr). Likewise, deep slip on the Imperial and Elsinore faults (5.3 ± 2.3 cm/yr) compares well with expected relative velocity of 5.5 cm/yr between the North American and Pacific plates (Atwater and Molnar, 1973).

Relatively recent large-scale diastrophism is shown by deformed geomorphic features throughout the Salton Trough, such as warped shorelines of ancient Lake Cahuilla which covered much of the trough earlier in Holocene time (Stanley, 1963; 1966). Elsewhere the land surface is being folded at present as is shown by anticlinal growth of small incipient hills near at least one active fault zone, and by closed playa basins throughout the southwest side of the Salton Trough (Sharp and others, 1972).

THE SAN ANDREAS FAULT ZONE

Northwest of the Salton Trough the San Andreas fault is a narrow, well-defined boundary between the North American and Pacific plates, but near the head of Salton Trough it splays southeastward into three major fault strands within a broad zone of faulting associated with transformed spreading centers in the Salton Trough and the Gulf of California (Lomnitz and others, 1970; Elders and others, 1972; Jennings, 1975; Crowell and Ramirez, Chap. 3, this volume).

Historic Seismicity

The largest historic earthquake attributed to the San Andreas fault proper in Salton Trough is the 1948 (M 6.5) Desert Hot Springs earthquake (Wallace, 1970). No surface displacement was attributed to this earthquake. Indeed, the only historic displacement on the San Andreas fault, as well as its substrands in Salton Trough, the Banning and Mission Creek faults, was about one centimeter of right slip dynamically triggered by the Borrego Mountain earthquake in May, 1968, in the Mecca Hills (Allen and others, 1972).

Although there have been three other earthquakes between 1934 and 1961 in the magnitude range of from 5.0 to 5.9, the San Andreas fault in Salton Trough is characterized by low seismicity (Allen and others, 1965; Wallace, 1970; Allen and Whitcomb, 1978; Fuis, 1978). During the six-month period 1 October 1977 to 31 March 1978, the "Southern California Seismic Array" located 3,897 events. Of fifteen $M \geq 4.0$ earthquakes, all but two were in the Imperial Valley area, but few earthquakes occurred along the southern San Andreas (Fig. 6). The most striking feature of the six-month seismicity is a conspicuous "gap" centered on the San Andreas fault N of the Salton Sea (Allen and Whitcomb, 1978). According to Allen and Whitcomb, this feature appears to have existed since at least 1950 and may represent a temporal seismic gap.

Geomorphology

Much of the southern San Andreas fault is characterized by the presence of classic examples of deformed geomorphic features indicative of repeated Holocene movement. Deflected and offset major drainages, scarps, dissected sag ponds, groundwater barriers, anomalous stream profiles, shutter ridges, beheaded streams and repeatedly offset stream channels are especially well exposed in the tectonic culminations of the Indio, Mecca and Durmid Hills.

Offset stream channels provide the most convincing geomorphic argument for repeated horizontal slip in Holocene time (Norris, Keller and Meyer, 1979). In the Indio Hills several small stream channels a meter or so in width have evidently been progressively offset from their source in several discrete events. A small drainage basin, headed entirely within the fault gouge of the main fault zone, is the only apparent source for all of the channels. The channels are progressively wider and longer closer to the present drainage channel indicating growth of the small drainage basin through time as faulting has occurred. Except for the present drainage channel, all of the channels are beheaded by the fault and have no immediate source. One explanation for this phenomenon is that repeated five- to seven-meter horizontal displacement events coupled with a lesser component of vertical movement were probably associated with large earthquakes along this section of the fault system and thus progressively offset an active stream channel system.

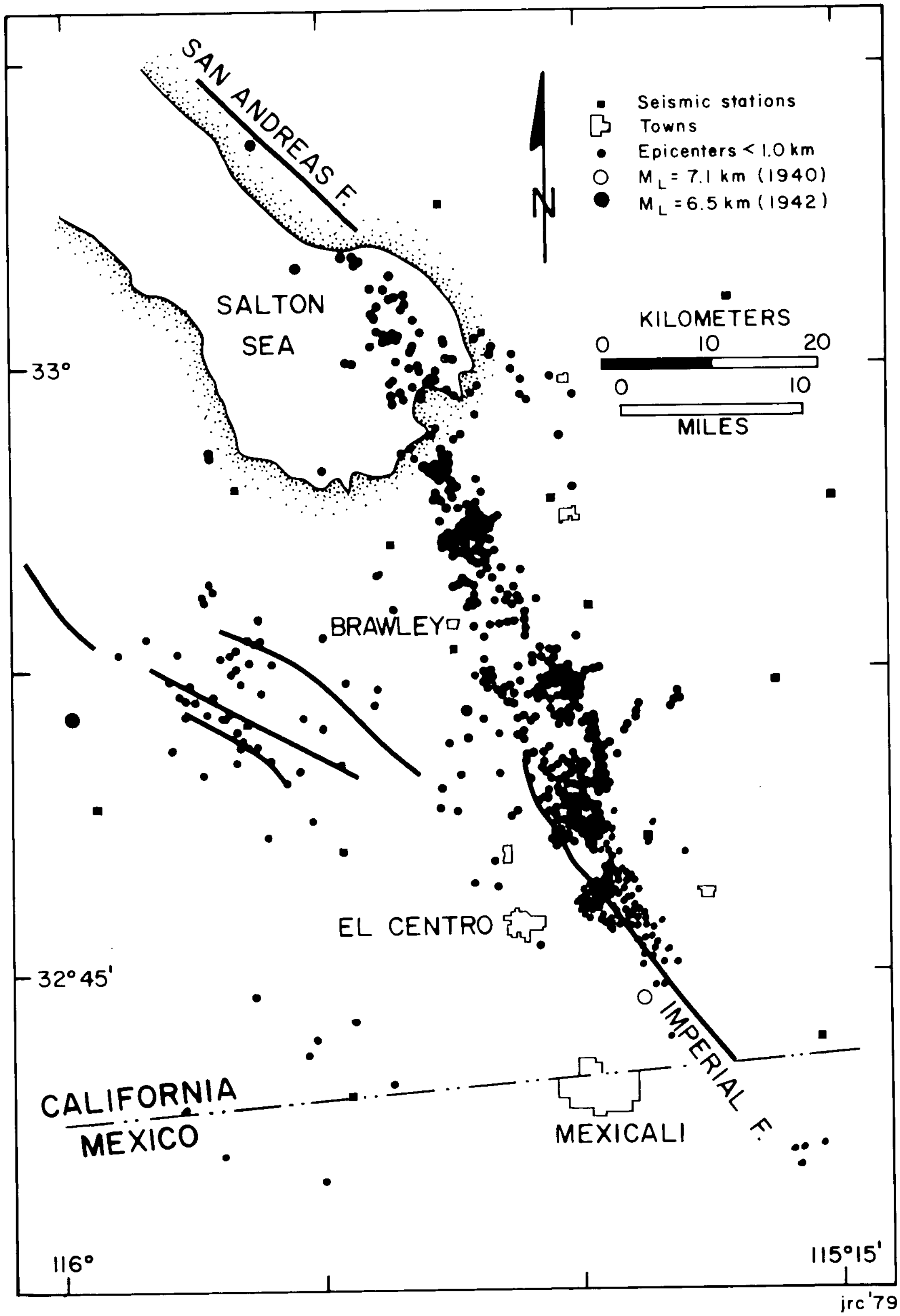


Fig. 6. Seismicity of Imperial Valley, 1973-78, showing earthquake epicenters located with a precision of 1 km or less. Redrawn by permission from map compiled by Livermore Berkeley Laboratory (Vonder Haare, personal communication, 1979) from Johnson (1979).

THE SAN JACINTO FAULT ZONE

The San Jacinto fault zone, a predominantly northwest-trending complex system of faults including the San Jacinto, Buck Ridge, Hot Springs, Casa Loma, Thomas Mountain, Claremont, Clark, and Coyote Creek faults, is characterized by its continuity, straightness, high seismicity, and right slip. It may currently be the most active member of the San Andreas fault system (Sharp, 1967; Terres and Crowell, Chap. 2, this volume). Diverging from the San Andreas fault near Wrightwood, the San Jacinto fault zone strikes southeast through San Bernardino and along the west side of the San Jacinto and Santa Rosa Mountains to within a few miles of Ocotillo Wells where it steps left to the Superstition Hills-Imperial fault zone. Cumulative right separation is about 24 km (15 miles) (Sharp, 1967).

Numerous primary fault features such as deflected drainage and scarps indicate recurrent Holocene movement along nearly the entire length of the fault (Sharp, 1967). Data from trenching after the 1968 Borrego Mountain earthquake document many episodes of Holocene movement along the Coyote Creek fault (Clark, Grantz, and Rubin, 1972). Trenches across the Casa Loma strand in Riverside County also cut Recent alluvium (Proctor, 1962; Hart, 1979). These factors, along with its historic seismicity and present strain rate, show sustained activity of this fault in Recent geologic time.

Historical and Holocene Seismicity

Between 1899 and 1979, seven major earthquakes ($M > 6$) occurred along the San Jacinto fault zone (Allen and others, 1965; Clark, Grantz, and Rubin, 1972). Only two of the earthquakes, the 1918 (M 6.8) and the 1968 (M 6.4) events, had documented surface displacements associated with them. The average return frequency for the seven earthquakes is 11.4 years. Using these historic data and Wallace's (1970) relationships among the return frequency, the total length of the fault zone, and the length of the rupture for a given event, Clark, Grantz, and Rubin (1972) suggested that, for any section of the fault, a magnitude 6 or larger earthquake should occur on the average of every 200 years. This figure agrees closely with the return frequency established from trench studies across the Coyote Creek fault after the 1968 earthquake. Clark, Grantz, and Rubin (1972) documented as many as 17 events in about 3000 years based upon C^{14} dating of pelecypod and gastropod shells from Lake Cahuilla strata within the trench. However, in recent work along the same fault, Sharp has found large errors in apparent ages of shells from lake deposits determined from C^{14} dating of peat strata in two recently opened trenches. He has suggested that the 200-year estimate of the recurrence of 1968-sized earthquakes on the Coyote Creek fault (Clark, Grantz, and Rubin, 1972) is too large by a factor of 3 to 4. Further work is being undertaken at present to establish a correction schedule for the apparent ages (Sharp, 1978).

In addition to the major earthquakes, numerous smaller earthquakes have occurred frequently along the San Jacinto fault zone (Allen and Whitcomb, 1978; Fuis, 1978). Most of the smaller events have been detected only in the last few years, primarily due to the increase in the density of seismic recording instruments in this area.

Strain and Creep on the San Jacinto Fault Zone

Triangulation measurements across the whole Salton Trough region from 1941 to 1954 indicate that much of the strain release is taking place across the San Jacinto fault, not the San Andreas fault (Whitten, 1956). The data, surveyed over a very short period of time (14 years), indicate an annual rate of 2.5 cm/yr dextral strain parallel to the fault zone near Borrego Valley. A more recent trilateration survey (1972-1977) indicates 5 cm/yr of dextral strain across the entire Salton Basin, with the San Jacinto accounting for 1.7 ± 0.9 cm/yr (Savage and others, 1979).

Creep is not recognized on most parts of the fault. Where observed, the relationship to seismic events is not certain (Wallace, 1970). Much afterslip occurred on the Coyote Creek fault following the 1968 Borrego Mountain earthquake: Burford (1972) documented as much as 18 cm of afterslip on the central break (following 13 cm of initial displacement) and 0.5 cm on the northern break (following 38 cm of initial displacement). Keller and others (1978) documented 11 cm of creep between 1970 and 1972 near Anza, north of the 1968 break, but inasmuch as their monuments (primarily nails in trees or telephone posts) may not be reliable, additional work needs to be done in this area to determine if creep is actually taking place. More recently, Harsh (1977) reported that the rate of aseismic slip on the Coyote Creek fault between 1971 and 1977 had stabilized to 5 mm/yr, which is consistent with Keller and others (1978), and may represent steady-state creep rather than afterslip.

Late Pleistocene and Holocene Geomorphic Evidence for Activity

Sharp (1967) considers that the San Jacinto fault has had a major effect on the physiography of the northern Peninsular Ranges. Many major topographic features, such as aligned valleys and major drainages, are produced or controlled by this fault. On these large-scale features are superposed numerous fault-produced topographic features such as deflected drainage, truncated spurs, shutter ridges, scarps, and sags indicative of probable Holocene movement. Major stream channels have been offset 0.7 km in an estimated 30,000 years (Sharp, 1967). There can be no doubt based on geomorphic evidence of the high level of late Pleistocene and Holocene activity of this fault system.

THE ELSINORE FAULT ZONE

The Elsinore fault zone is a system of predominantly right-slip faults extending northwestward from Ocotillo west of El Centro to Whittier near Los Angeles (Jennings, 1975). An appreciable number of earthquakes is associated with the Elsinore fault system indicating its activity and potentially hazardous nature (Langenkemp and Combs, 1974). In addition, many of the faults, primarily the Chino fault, the Whittier fault, and those fault segments which make up the Elsinore fault, have scarps, deflected or offset drainage, truncated spurs, faulted alluvium, and sags (Weber, 1977; Mann, 1955; Clark, 1972; Kennedy, 1977) which are evidence of activity in late Pleistocene and Holocene time. Cumulative right-separation is about 40 km (24 miles) (Lamar, 1961; Sage, 1973).

Historical Seismicity

The largest earthquake attributed to the Elsinore fault system is the May 1910 Temescal Valley earthquake (M 6) just north of the Lake Elsinore depression (Richter, 1958). Between 1961 and 1971, over 150 earthquakes were recorded along the Elsinore fault system registering between M 3.0 and 4.5 (Langenkemp and Combs, 1974). Of these, most were from magnitude 3.0 to 3.5, 15 were from magnitude 3.5 to 4.0, and 7 were from magnitude 4.0 to 4.5. Their distribution ranged from the southernmost extent of the fault up to and along the Whittier fault. Most of the southern earthquakes clustered just east of the San Diego-Imperial County line in the Carrizo Valley and Vallecito Mountains area, occurring as an aftershock sequence following the 1968 Borrego Mountain earthquake (Allison and others, 1978). Langenkemp and Combs showed seismic activity increased from north to south along the Elsinore fault system with 0.5 events per day at the north end and 3.7 events per day at the south end. They also concluded that these events were generally shallower than 5 km except in the Agua Caliente Springs area where hypocenters were as deep as 12 km. The September 13, 1973, earthquake (M 4.5) at Agua Caliente Springs and its aftershock sequence on the southern part of the fault provided a rare opportunity to study an area previously subjected to variable tectonic interpretations (Allison and others, 1978). Four portable seismographs were set up around the epicentral area from 12 to 26 hours after the main shock; seven more were installed four days after the earthquake. Thirty-five of 45 subsequent events could be termed aftershocks. The earthquake series was associated with the south branch of the Elsinore fault in the Agua Caliente Springs area. Focal mechanisms indicate right slip on a northeast-dipping stretch of this fault (Allison and others, 1978).

Late Pleistocene and Holocene Geomorphic Evidence of Activity

Many primary geomorphic features indicate late Quaternary faulting along the Elsinore, Whittier, and Chino faults. The northern Elsinore fault zone displays many examples of deflected drainage and fault scarps (Weber, 1977; Engel, 1959). Weber documented faulted landslide deposits, faulted older alluvium and relict paleosols, truncated and faceted spurs, and overly steepened alluvial fans along this section of the fault. In addition, Mann (1955) described faulted river terraces and faulted low-level fanglomerates. The alluvial fans and terrace gravels have not been dated.

Along the southeastern Elsinore fault zone, fewer primary features or evidence for recent faulting are found except along a 15 km section at the San Diego-Imperial County line where Clark (1975) describes "the impressive continuity of very recently offset surfaces and channels."

The Whittier fault, besides displaying primary surficial faulting features, also shows manifestations of activity in Holocene time according to evidence in trench exposures (Hannan and Lung, 1979).

The Chino fault also displays active primary features such as deflected drainage and scarps in the Puente Hills (Weber, 1977) and variable citrus tree growth there indicates the presence of a groundwater barrier. Trenches across the Chino fault demonstrate Holocene movement along the fault in western Corona (Weber, 1977).

THE IMPERIAL AND RELATED FAULTS

The Imperial fault zone, a predominantly northwest-striking complex system of faults including the Superstition Hills, Imperial, Brawley, and Cerro Prieto faults (Fig. 8) is characterized by its high seismicity, straightness, and right slip. Believed by many geologists to be the southern extension of the San Jacinto fault zone, these faults are considered separately here because of the apparent lack of surface continuity with the San Jacinto fault. Seismicity data, however, show that the Imperial fault may be linked to the San Andreas fault by way of the Brawley fault (Hill, Mowinckel, and Peake, 1975; Fuis, 1978; Fig. 7).

The Imperial fault was virtually unknown prior to the 1940 (M 7.1) earthquake, primarily because a small scarp along part of the fault was not recognized as a tectonic feature. Moreover, there was no historic record of surface faulting associated with the 1915 and 1917 earthquakes (M 6) which were attributed to this fault. Some work has been done since 1940 to determine previous seismicity (Sharp, 1977, 1978).

Many of the earthquakes before 1940 are only suspected in hindsight of having occurred on the Imperial fault, because the strongest motions and greatest damage were near this fault (Ulrich, 1941; Balderman and others, 1978). One and one-half centimeters of surface displacement occurred in conjunction with the 1966 (M 3.6) earthquake on the Imperial fault (Brune and Allen, 1967) as well as comparable displacements dynamically triggered by the Borrego Mountain earthquake in 1968 (Allen and others, 1972). Trenching across the 1940 break (Burford and Goulty, in Sharp, 1977; Sharp, 1977, 1978) shows that strata within 1.5 m of the surface probably suffered at least two episodes of large-scale slip prior to the 1940 earthquake. Carbon from the 1.5 m level, now being dated, will define a maximum time for at least two seismic events associated with major slip on the Imperial fault.

The Superstition Hills fault is situated between the San Jacinto and Imperial faults in en echelon fashion. Historic seismicity accompanied by ground rupture along nearly the entire length of the fault has allowed precise determination of its location. Triggered by the 1968 Borrego Mountain earthquake on the Coyote Creek fault, the Superstition Hills fault broke along nearly its entire known length (Allen and others,1972). Similar events on other faults caused displacement in 1965 and 1969 (Jennings, 1975). The 1951 (M 5.6) earthquake on the Superstition Hills fault caused small local displacement (Allen and others, 1965; Jennings, 1975). The September 1971 (M 5.3) earthquake, centered on the Superstition Hills fault, resulted in displacement only on the Imperial fault (Clark, 1972).

The Cerro Prieto fault in Mexico steps right from the Imperial fault a few miles south of the International Boundary. It has been the probable source for at least ten moderate to large earthquakes since 1903 (Ulrich, 1941), including the Fort Yuma earthquake of 29 November 1852 (Balderman and others, 1978). The epicentral areas were determined largely from sparse intensity data and, in some cases, instrumentally

The Brawley fault, known primarily from recent seismic data (Allen and Whitcomb, 1978; Fuis, 1978; Hill, Mowinckel, and Peake, 1975; Johnson and Hadley, 1976) (see Fig. 7) evidently steps right from the San Andreas fault at the southeastern end of the Salton Sea (Meidav, 1968; Meidav and Howard, 1979) and strikes SSE where it passes through the city of Brawley and merges with the Imperial fault northeast of Imperial (Sharp, 1976). The Brawley fault may have been the fault responsible for generating the 1906 (MM = VIII) and 1930 (MM = VIII) earthquakes, judging from the fact that Brawley was the hardest hit town in the vicinity for both of these shocks (Ulrich, 1941). Surface rupture was not documented for either event. A number of earthquake swarms have been located recently on the Brawley fault (Fuis, 1978; Hill, Mowinckel, and Peake, 1975; Johnson and Hadley, 1976; Allen and Whitcomb, 1978; Keller, Chap. 5, this volume), yielding a much better determination of its location and showing a right-stepping en echelon arrangement of faults striking northward to the south end of the Salton Sea.

Strain and Creep

Strain release across the Imperial fault zone was reported to be 8 cm/yr for the 1941 to 1954 period (Whitten, 1956). More recent surveys show that this figure is too high, being contaminated by the 1940 Imperial Valley earthquake. Savage and others (1979) documented 4.6 ± 2.1 cm/yr of deep slip across the Imperial fault for the years 1972-1977, during which time there was no major seismic activity.

Creep along the Imperial fault has been measured in recent years by several workers (Gilman and others, 1977; Anderson and others, 1977; Burford, 1977; Keller and others, 1978; Goulty and others, 1978). The conclusions generally agree that the fault has been creeping in episodic fashion at 8 to 10 mm/yr over the past decade (Burford, 1977). Superposed on steady-state creep at very low background rates are large and small creep events (up to 25 mm and 0.3 mm, respectively) every few years (Goulty and others, 1978). Creep has also been reported on the Brawley fault at an average slip rate of 5 mm/yr (Savage and others, 1979). Less than 2 mm of creep was reported on the Superstition Hills fault between 1968 and 1977 (Goulty and others, 1978). Creep measurements have not been undertaken south of the International Boundary.

Other Active (?) Faults

Fresh, long subparallel cracks in alluvial fan deposits were found in 1976 overlying the Salton Creek fault (Buckley, Magee and Hayden, 1977). No earthquake activity could be shown to be related spatially or temporally to the cracks, but a small aperture trilateration array was established across the zone of cracks, and in a 7-month period, 11 mm of left separation took place. Inasmuch as the cracks and the sense of horizontal separation agree with what is known about the geometry and sense of slip on the Salton Creek fault, Buckley, Magee and Hayden (1977) believe the cracks are tectonic, but aseismic, in origin. They point out, however, that an undetermined amount of withdrawal of groundwater takes place for agricultural use from nearby wells; thus the cracks may be due to nontectonic subsidence.

Chapter 5

IMPERIAL VALLEY EARTHQUAKE SWARMS

by

B. Keller

ABSTRACT

The Imperial Valley and northern Gulf of California are characterized by swarms of moderate earthquakes which may occur very close together in time and space. Such swarms typically consist of a few tens to a few hundred distinguishable events. Detailed studies of some recent swarms, made possible by dense instrumental coverage, show that the hypocenters migrate with time along the trends of previously recognized or inferred faults or seismic lineaments, as well as along some previously unrecognized structures.

INTRODUCTION

Earthquake swarms, as opposed to individual events, have been inferred to be associated with magmatic processes in some way (Ward, Budmundur, and Drake, 1969; Weaver and Hill, 1979). To be sure, geothermal regions in Imperial Valley and Quaternary volcanic rocks at Obsidian Buttes support that inference in Imperial Valley, but no surface magmatic activity has occurred there in historic time in spite of the many swarms.

Richter (1958, p. 72) reported the occurrence of swarms in 1934, 1950, and 1955. A lapse in seismicity seems to have followed the 1940 Imperial Valley earthquake (M 7.1), which was associated with considerable surface faulting (Ulrich, 1941; Trifunac and Brune, 1970; Sylvester, 1979). More recently Thatcher and Brune (1971) described a swarm in the northern Gulf of California near Wagner Basin. Their listing of swarms prior to 1971 shows that swarms tend to group together in time in both

Wagner and Delfin Basins, but no clear correlation is evident between these in the Gulf and those in the Imperial Valley. A dense network of seismometers recorded four swarms in Imperial Valley from June 1973 to May 1974: two on the Imperial fault, one 8 km north of Brawley, and one at Obsidian Buttes. Two studies of more recent swarms on the Brawley fault, in January 1975 and October-December 1976, are described below.

DEPTHS AND FOCAL MECHANISMS

The depths assigned to swarm hypocenters depend on the quality of seismic records and on the crustal model used for calculation. It is clear, however, that all of the events are quite shallow, even by Californian standards. Calculated depths range from the surface to 14 km, but most investigators infer that the hypocenters are actually from 4 to 6 km deep (Meidav and Howard, 1979), corresponding approximately to the base of the sediments filling the Imperial Valley.

Focal mechanisms for earthquakes in the various swarms show both strike- and normal-slip faulting. Commonly, the strike-slip mechanisms are on the northwest-trending lineaments, whereas the normal mechanisms are on the conjugate northeast-trending features, but there are many exceptions to this generalization. Strike-slip mechanisms on northwest-trending features are consistent, of course, with right slip of the San Andreas fault system.

RECENT SWARMS

Location and migration history of two recent swarms or swarm clusters are depicted in Fig. 7. The swarm of 23-31 January 1975 is described by Johnson and Hadley (1976) and the associated surface faulting is described by Sharp (1976). The activity was most intense for four days, with 75 events $4.7 > M_L > 3.0$ and 264 events of $M_L > 1.5$. Activity started on a northeast lineament near the Brawley fault. When the activity reached the Brawley fault, the largest event ($M_L = 4.7$) occurred and was accompanied by surface rupturing south of Brawley where Keystone Road was offset 0.2 m vertically (east side relatively

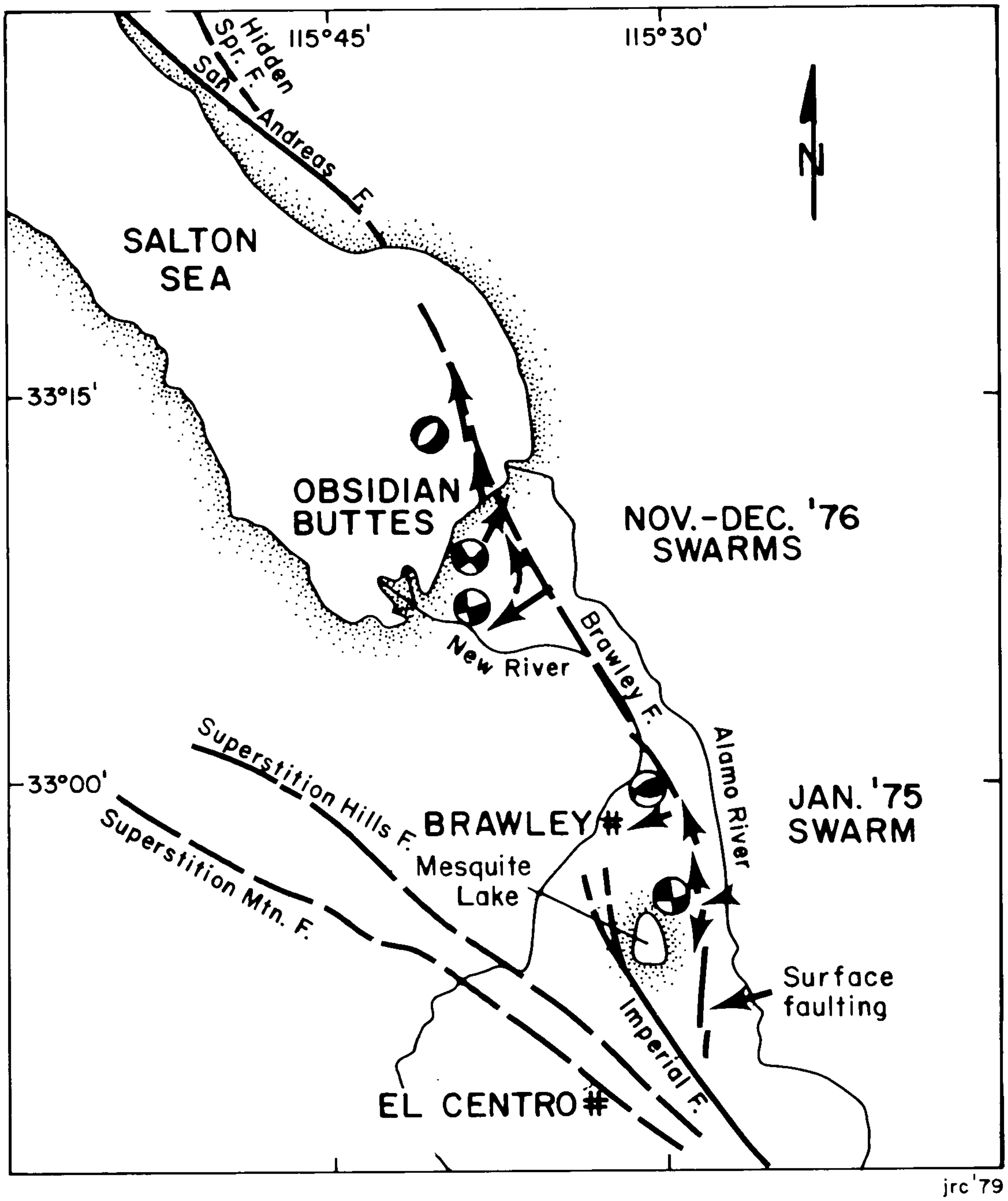


Fig. 7. Map of Imperial Valley area showing selected focal mechanisms and event migration directions for two earthquake swarms on the Brawley fault, 1975, 1976.

up). The time of the offset was reported by a farmer who drove across the fault every hour and noticed a bump on one particular crossing which was not present earlier. The seismicity then migrated both north and south at about 0.5 km/hr. The north branch had a spatial gap in the middle but continued temporally north of the gap, ending with a number of events on a 3 km-long, northeast-trending feature near Brawley on the extension of the splayed traces of the 1940 Imperial fault west of Mesquite Lake (Fig. 7). Most of the surface faulting (10.4 km long) was south of the earthquake epicenters. Earthquakes later occurred south of the surface ruptures on 31 January between those breaks and the Imperial fault.

Three earthquake swarms occurred in November-December 1976 (Fuis and Schnapp, 1977). They were approximately on the Brawley fault but also defined two new lineaments at high angles to the fault. The overall sequence progressed temporally from south to north as shown by the arrows in Fig. 7. Activity in the first eight hours of November 4 was at the east end of the southernmost arrow, culminating in a $M_L = 4.9$ event. In the next hour seismicity spread to the west end of the arrow with an $M_L = 4.2$ event after three hours. For the next six days seismicity was mostly on this lineament, but toward the end of this period some events occurred near Obsidian Buttes to the north. The first swarm had 213 events, with nine earthquakes of $M_L = 4.0$ in the first twelve hours. The second swarm commenced on November 11 at Obsidian Buttes, progressing from the south to the north end of the central thick arrow (Fig. 7) in two and one-half days. This swarm consisted of 62 events, the largest of which was $M_L = 3.4$. Seismicity was recorded near each of the first two swarms in the following month with one event near the third swarm. On December 17 the third swarm started 7 km north-northwest of Obsidian Buttes. Two days later the activity shifted 3 km farther along the same trend beneath the Salton Sea. There were 12 events in all. Normal faulting, shown by the focal mechanisms in the third swarm, indicates faulting complexity under this part of the Salton Sea. Apparently a deep seismic displacement migrating along the Brawley fault triggers seismicity on related structures at high angles to the fault.

Chapter 6

STRUCTURE OF THE SALTON TROUGH FROM GRAVITY AND SEISMIC REFRACTION DATA

by

B. Keller

ABSTRACT

The depth to basement and the thickness of the crust beneath the Salton Trough may be inferred from gravity and seismic refraction data. A northwest-oriented, elongate welt of high gravity values is present in Imperial Valley as the landward projection of high gravity values along the length of the Gulf of California. It is interpreted variously as being caused by the presence of high-density mafic igneous rocks injected along the axis of the spreading plate boundary. Also apparent is the thickening of the crust from Imperial Valley northwest to Coachella Valley.

Noteworthy features of the Salton Trough are the east-tilted half graben beneath Coachella Valley which is about 5 km deep adjacent to the San Andreas fault; and an apparent pull-apart graben, also 5-6 km deep, centered beneath Mesquite Lake in Imperial Valley.

That the Salton Trough is a large physiographic depression is dramatically shown by the painted stripes at "sea level" high on silos near Brawley and El Centro. The stripes are from 30 to 40 m above the ground. But the Salton Trough is also a deep sedimentary basin, which is geophysically and geographically subdivisible into the southern Imperial Valley and the northern Coachella Valley. Imperial Valley, presumably the deepest part of the trough, is characterized geophysically by a gravity high, which is the opposite of what one would expect for a deep sediment-filled basin. The Coachella Valley, on the other hand, is characterized by a gravity low. Here we review what gravity measurements and seismic refraction studies have yielded concerning the deep structure of the two parts of the Salton Trough.

In the Imperial Valley, the Salton Trough Bougher gravity values are from 20 to 40 mgal higher than the regional average values, and form a welt of high gravity values trending northwest to the middle of the Salton Sea (Fig. 8). Two of the highest values, however, are off the axis of the welt: one near Yuma (-10 mgal) and the other over the Sierra de los Cucapahs in Mexico (-20 mgal). Obsidian Buttes (-20 mgal) are centered over the highest gravity value on the welt. Volcanic rocks are present at the surface here, but the gravity maximum is broader than the area of the buttes. One interpretation is that more igneous or metasedimentary rocks are present at shallow depths. Ground magnetic data (Kelley and Saske, 1936) and aeromagnetic data (Griscom and Muffler, 1971) also show that the size of the pluton beneath Obsidian Buttes is much greater than that which would be caused by the five small volcanoes (Meidav and Howard, 1979). N, W and E of the buttes, the gravity decreases steeply to values more typical of regional crustal values.

Pronounced linear gravity features are associated with the Elsinore and San Jacinto fault zones where locally uplifted steep-sided basement blocks are separated from one another by deep alluvial fill (Fig. 8). A very steep gravity gradient bounds the west side of the Sierra de los Cucapas adjacent to Laguna Salada (Fig. 8) which has a sediment fill of about 5.8 km in depth (Biehler, Kovach and Allen, 1964).

Several notable finer-scale features are defined by gravity around the borders of the Salton Trough. Coachella Valley has a gravity low with very steep sides. The abrupt gravity gradient along the San Andreas fault adjacent to the Mecca Hills (Fig. 9) suggests a minimum vertical separation of the basement of 3.2 km and possibly as much as 5 km (Biehler, 1964; Biehler, Kovach and

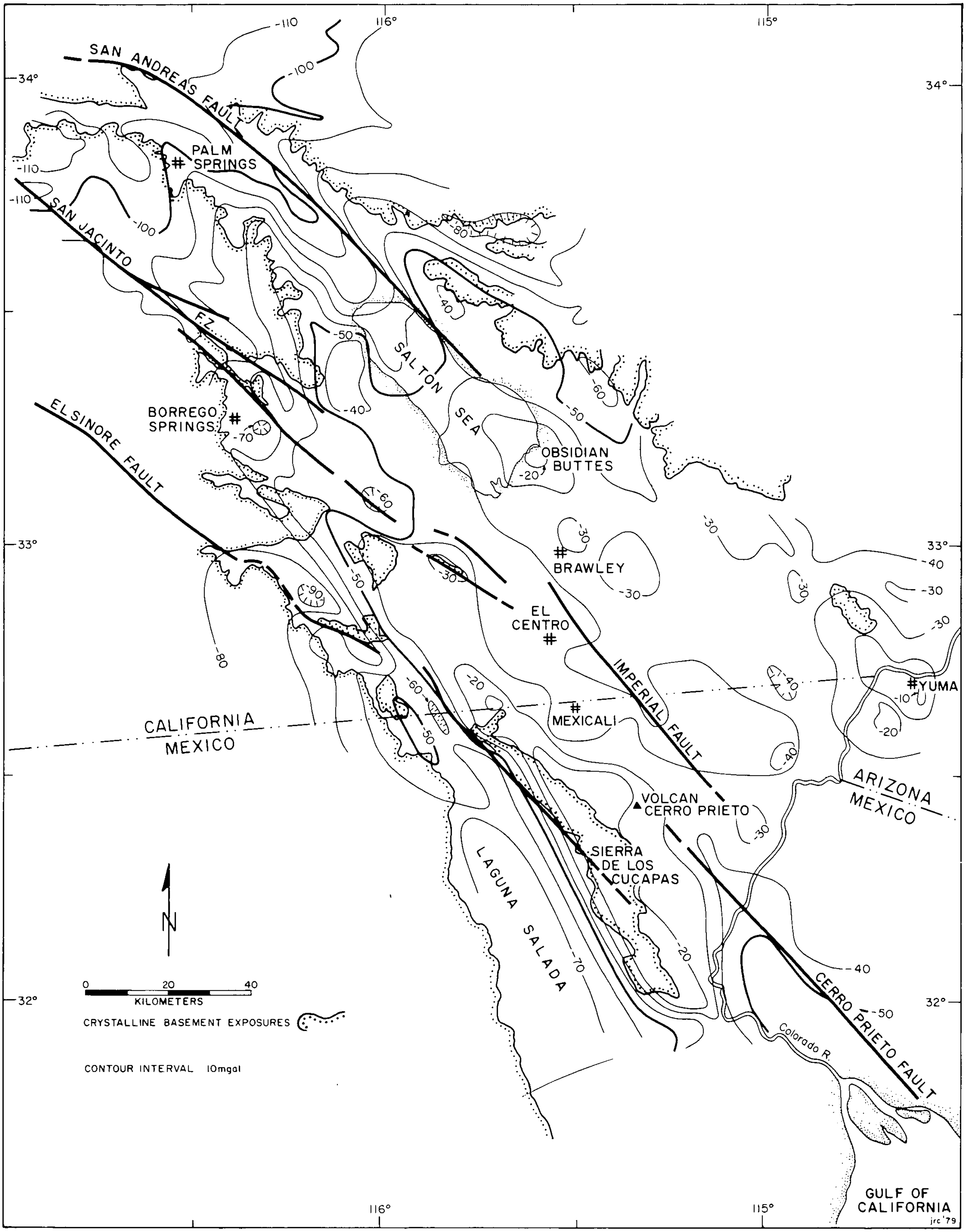


Fig. 8. Simple Bouguer anomaly map of Salton Trough. Redrawn from Biehler, Kovach and Allen (1964).

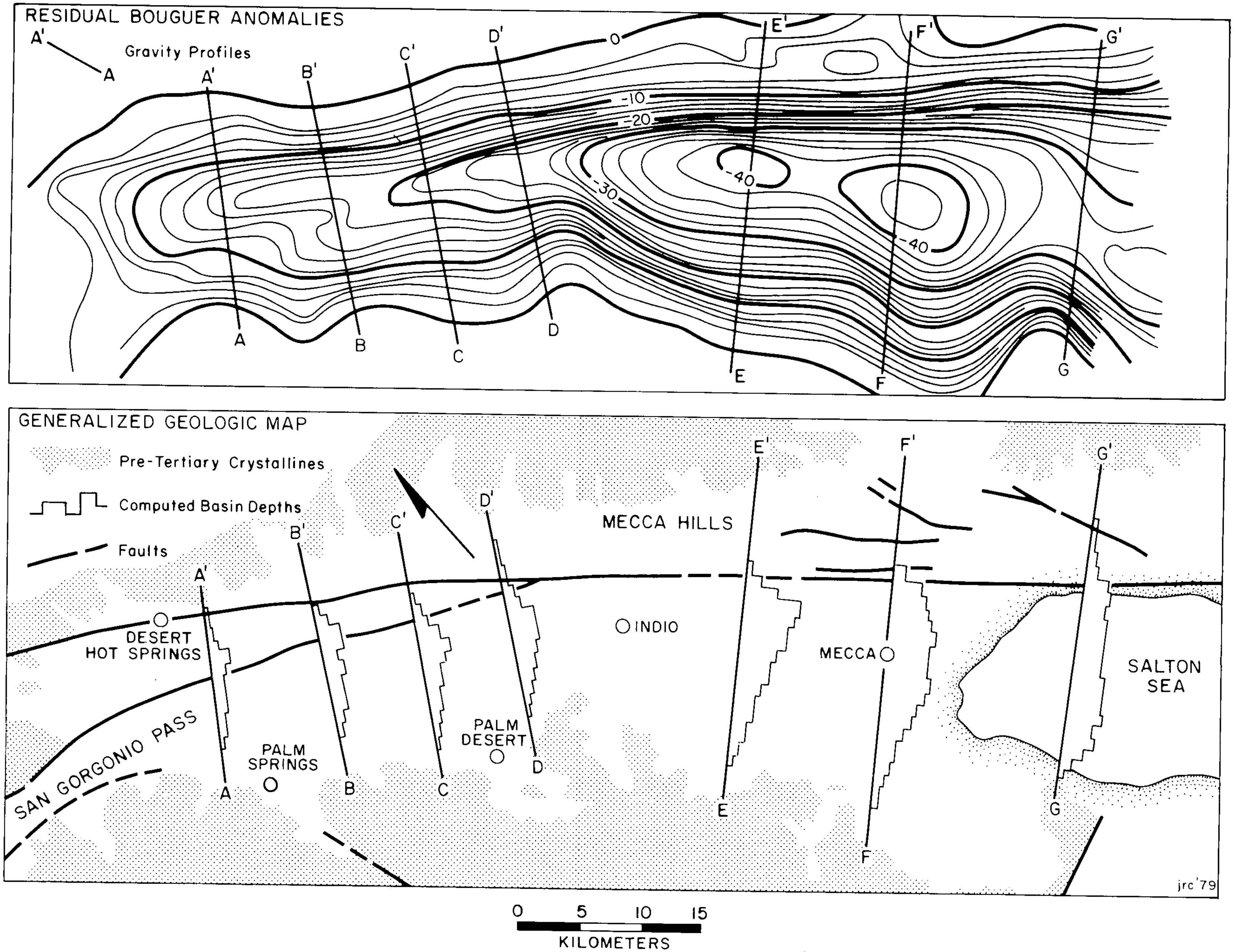


Fig. 9. Residual Bouguer anomalies and computed basin depth profiles across Coachella Valley. Redrawn from Biehler (1964).

Allen, 1964). This gravity feature disappears southeastward at the end of identifiable faulting at the northeast edge of the Salton Sea. Sharp and others (1972) has argued that gravity data suggest that a major fault is also present along the southwest side of Coachella Valley.

The regional gravity of the Gulf of California is shown in Fig. 10. A correction has been made for sedimentary fill so that the contours should be indicative of crustal thickness or density variations. The sediment correction in the Salton Trough is about +50 mgal, thus 0 mgal contour reaches north into the area in Fig.10. The principal feature of this map is the linear gravity high which extends from the length of the Gulf of California into the Salton Trough where it terminates abruptly. The most straightforward interpretation of this feature is that it represents the depth to the mantle.

Structurally the Gulf of California is generally regarded as a modern oceanic spreading plate boundary, the opening of which is propagating northwestward toward and into the Salton Trough. At its southern end the Gulf is floored by normal oceanic lithosphere; there the Moho is interpreted from seismic data to be about 12 km below sea level. The Moho beneath the Salton Trough is deeper. No convincing seismic evidence exists indicating the exact depth, but the depth has been interpreted from gravity data to dip from 14 km at the International Boundary to 20 km beneath Coachella Valley (Biehler, Kovach, and Allen, 1964). Thus the peculiar nature of a deep sediment basin with a gravity high may be viewed as a rift where low-density sediments cover young, high-density material that has welled up at depth along the axis of the rift.

Seismic refraction studies also yield insight on the deep structure of the Salton Trough. Early studies found that the sedimentary fill is at least 5 km thick in the central part of the trough (Biehler, Kovach and Allen, 1964). More recently the U.S. Geological Survey has performed an extensive refraction study of the Imperial Valley (Fuis, Mooney and Healey, 1979). Some of the results of this study are shown in Fig.11. The contours of delay time show seismic delays at receiver locations. Interpretation of the data shows that the west side of the trough is characterized by small irregular domains of low delay times indicative of shallow basement blocks, probably downfaulted blocks of Peninsular Range basement rocks. The contours along the east side of the trough are much smoother. A sequence of sediments as thick as 6 km is apparent from the large delay times in the center of the trough in the vicinity of Mesquite Lake. The topographic depression there and the large delay times can be interpreted as showing a deep rift in the crust or a very low velocity sediment fill, both of which might be expected over a spreading rift. If

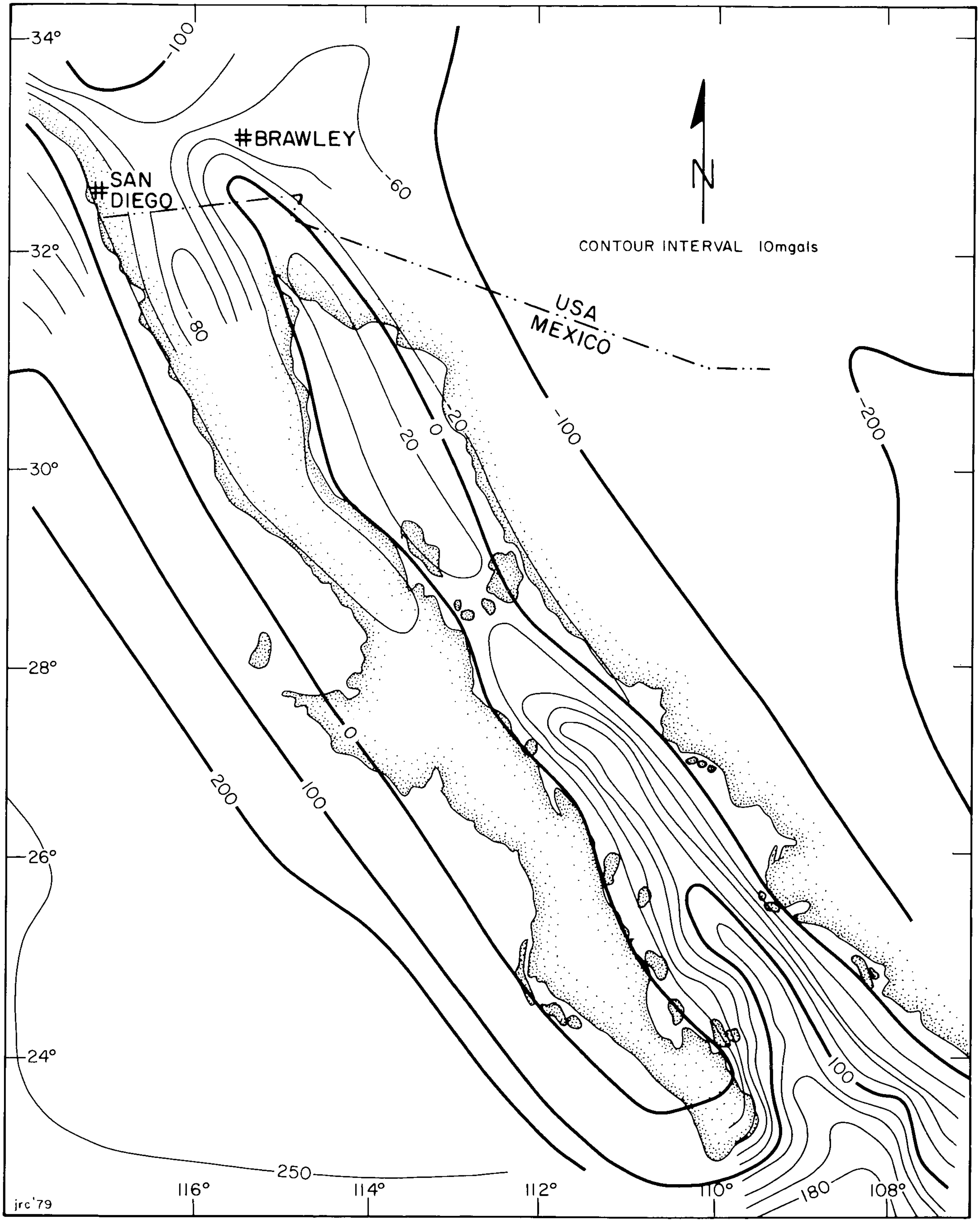


Fig. 10. Sediment corrected Bouguer anomaly map of the Gulf of California regions. Contours in mgal. Compiled from Biehler, Kovach and Allen (1964), Harrison and Mathur (1964), Woollard and Strange (1962) and Biehler (unpub., 1979).

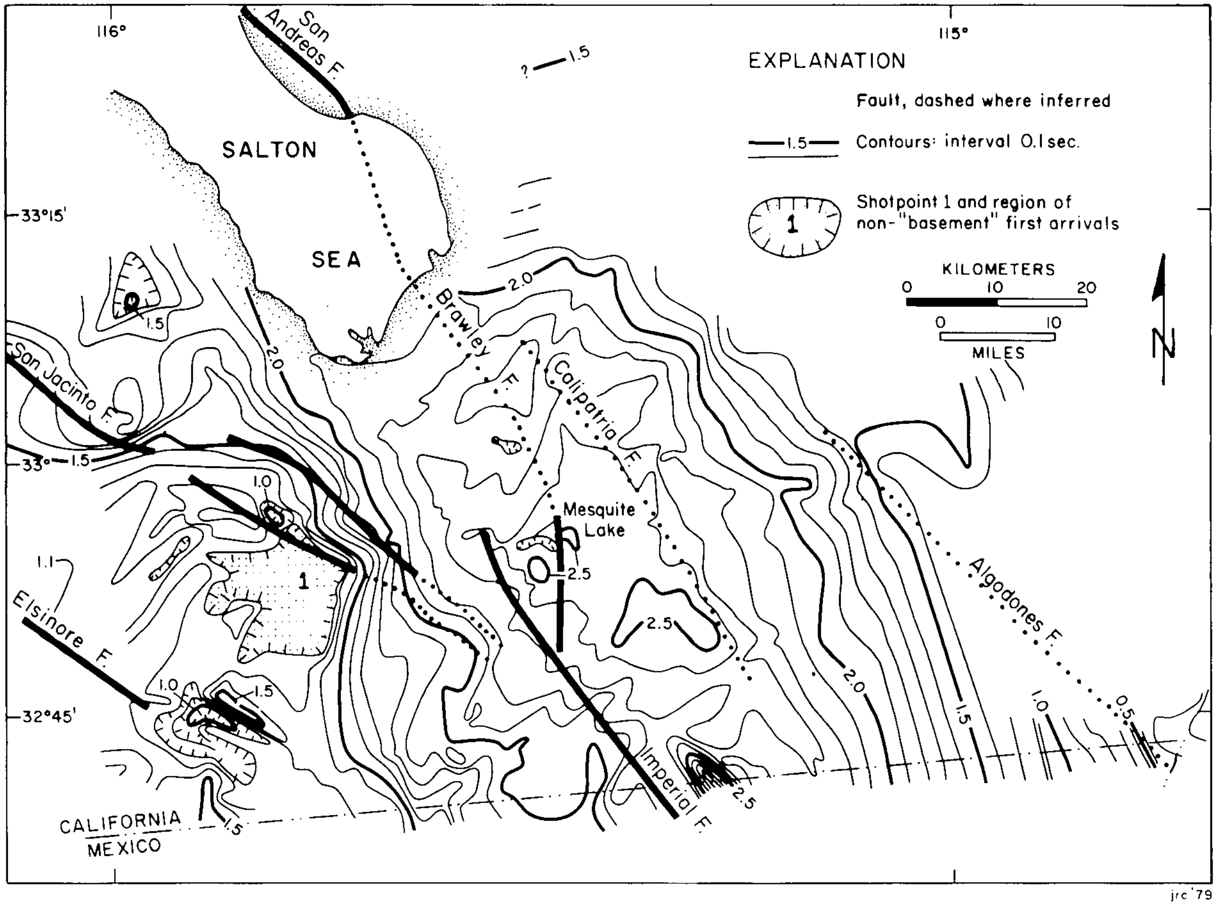


Fig. 11. Reduced travel time map from Shotpoint 1, Imperial Valley, California. Reduced travel time is actual travel time minus the quantity (km)/6 km sec, where (km) is the shot-to-recorder distance and 6 km/sec is an approximate basement refractor velocity. This map reflects the thickness of sediments overlying the basement refractor. Conversion of reduced travel times to actual sediment thickness requires detailed knowledge of seismic velocities. Preliminary studies indicate, for example, that the greatest sediment thickness, 7 km ± 1 km, is located at the 2.5 second contour in Mesquite Lake, near the center of the map. Maximum sediment thicknesses lie along the northwest-trending axis of the Imperial Valley. Changes in sediment thickness in small areas can be more accurately calculated than absolute thicknesses. For example, the change in sediment thickness from south to north across the San Jacinto fault, in the northwest corner of the map, is 2.5 km ± .2 km. After Fuis, Mooney and Healy, 1979.

the geometry of oceanic spreading ridges and transforms can be applied to this area (Lomnitz and others, 1970; Elders and others, 1972; Crowell and Terres, Chap. 2, this volume), then Mesquite Lake is the surficial expression and center of a relatively small pull-apart bounded by the Brawley and Imperial faults.

Taken together, the gravity and seismic refraction data indicate that Coachella Valley has the form of an asymmetric graben whose deepest part is along the northeastern side adjacent to the San Andreas fault. Coachella Valley shoals slightly toward the Salton Sea which overlies a transitional zone between Coachella and Imperial Valleys. Imperial Valley is also a tilted half-graben with a relatively planar eastern surface and with its deepest part on the western side against the San Jacinto fault zone. A pull-apart floored at least in part by young mafic igneous rock lies in the center of the valley beneath Mesquite Lake. The Salton Trough deepens as the depth to the mantle decreases from Coachella Valley southward across the Imperial Valley to the Gulf of California.

Chapter 7

BASEMENT ROCKS OF THE SALTON TROUGH REGION

by

Arthur G. Sylvester and Michael Bonkowski

ABSTRACT

The Salton Trough lies between two provinces of pre-Neogene basement rocks that contrast markedly with one another in lithology, age and evolution. These rocks also underlie the margins of the Salton Trough, and knowledge of the distribution of particularly distinctive rocks and rock suites in place and as clasts in derived conglomerates permits determination of offset on several major faults in the region.

West of Salton Trough in the Peninsular Ranges, calc-alkaline plutonic rocks constitute the composite Southern California batholith of Early and Middle Cretaceous age. This batholith intrudes metasedimentary and metavolcanic rocks of Mesozoic and probable Late Paleozoic age, and is itself overlain unconformably by Upper Cretaceous, Paleocene and Eocene and younger sedimentary and volcanic rocks. The batholithic rocks range from gabbro to granite; exposures represent mesozonal emplacement depths.

The mountains along the northeast margin of Salton Trough are underlain by a variety of Precambrian and Mesozoic metamorphic and plutonic rocks that have been intruded by granitic and hypabyssal rocks in both Mezozoic and Cenozoic times. The Mesozoic plutonic rocks are compositionally related to the Sierra Nevada batholith rather than the Southern California batholith just across the trough. The rock suite is distinctive, and includes anorthosite, syenite and related rocks, which document up to 300 km of right displacement on the southern part of the San Andreas fault.

INTRODUCTION

The Salton Trough separates two contrasting physiographic, lithologic, and structural provinces: (a) the Peninsular Ranges west of the trough, and (b) the eastern Transverse Ranges and Colorado Desert to the east, represented chiefly by the Little San Bernardino, Cottonwood, Orocopia, and Chocolate Mountains. Here we summarize the general features of the crystalline basement that constitute the framework for the trough. This terrane includes rocks ranging in age from Precambrian to mid-Cenozoic and as diverse in type as high-grade gneiss, marble, and sanidine-bearing rhyolite.

Although it is beyond the scope of this guide to describe these basement rocks in detail, they are vital to our understanding of the nature of the San Andreas-Salton Trough juncture. For example, features and distinctive rock suites within the basement terranes provide reference markers that in turn give clues to Late Cenozoic displacements. In fact, it is just such studies of unusual associations of basement sequences that indicate more than 300 km slip on the San Andreas system (Crowell, 1960). In addition, studies of the provenance of sedimentary units, especially conglomerates, are dependent on knowledge of the basement. Clast suites in some conglomerates document large displacements across major faults and also provide useful information on the timing of these displacements where the strata are dated (Crowell, 1952; Ehlig, Ehlert, and Crowe, 1975; Peterson, 1975; Crowell and Baca, Chap. 10, this volume).

THE PENINSULAR RANGES

The Peninsular Range Province is an uplifted and west-tilted crustal block that is topographically highest along the edge of the Salton Trough. It is broken into several elongate and subparallel blocks by major, northwest-trending faults. The Peninsular Ranges are underlain chiefly by metasedimentary and metavolcanic rocks of Late Paleozoic and Mesozoic age that are intruded by widespread representatives of the great composite Southern California batholith. Much of the Peninsular Ranges is covered by such dense growths of vegetation that "one frustrated investigator was moved to write, 'Where the steepness does not forbid the way, the chaparral everywhere disputes it'" (Jahns, 1954). Although somewhat obsolete in detail and in tectonic concepts, the best single source of general geologic information for the Peninsular Ranges is by Jahns (1954) from which some of the following description is abstracted.

Pre-batholithic Rocks

The oldest exposed rocks are widespread metasedimentary and lesser interlayered metavolcanic rocks which comprise very large, steep-dipping inclusions, pendants and screens within and around younger plutons of the Southern California batholith. The presence of quartzite and crystalline limestone together with phyllite, hornblende and mica schist, and quartz-feldspar schist and gneiss has led some writers to regard these rocks as Paleozoic in age because of their similarity to rocks of undoubted Paleozoic age in the eastern Transverse Ranges, but they are not yet dated directly. This sequence of rocks was regionally metamorphosed to the almandine amphibolite facies prior to the intrusion of the batholith. Contact metamorphism related to the batholith is quite local and clearly distinct from the regional metamorphism (Schwarz, 1969).

The Santa Ana Mountains in the northern end of the Peninsular Ranges are underlain by mildly metamorphosed strata as much as 7000 m (20,000 ft) thick composed largely of grey to brown argillite and slate with subordinate feldspathic quartzite and a few lenses of limestone and conglomerate. These rocks comprise the Bedford Canyon Formation (Larsen, 1948) and are middle to upper Jurassic (Bajocian to Callovian) in age (Silberling and others, 1961; Imlay, 1963, 1964; Criscione, Davis and Ehlig, 1978).

In the Winchester-Hemet area west of the San Jacinto fault, the Bedford Canyon Formation is depositionally and conformably overlain by a 4000 m (13,000 ft) sequence of mildly metamorphosed schist, amphibolite and quartzite grouped together as the French Valley Formation (Schwarz, 1969). Its regional extent beyond this area is unknown, nor is its depositional age known.

Elsewhere the Bedford Canyon Formation is overlain unconformably by slightly metamorphosed diabasic, andesitic and rhyolitic volcanic rocks comprising agglomerate, breccia tuff and lava flows interbedded with fine-grained argillaceous sedimentary rocks. These are termed the Santiago Peak Volcanic Rocks, making up a sequence estimated to range in thickness from 700 m (2300 ft, Gray, 1961) to 1400 m (4500 ft, Engel, 1959). They have been dated as Late Jurassic (Portlandian) in age on the basis of fossils in the interlayered sedimentary rocks and from K-Ar isotopic determinations (Fife, Minch and Crampton, 1967) or Early

Cretaceous (Colburn, 1973). Associated dikes, ranging from basalt to rhyolite in composition, are intruded by plutons of the Southern California batholith (Larsen, 1948), but locally andesitic dikes intrude diorite (Engel, 1959).

Batholithic Rocks

The Southern California batholith is a large, internally complex domain of calc-alkaline plutonic rocks. The batholith, extending northwestward from the southern tip of Baja California to Mt. San Jacinto at the north end of Salton Trough is more than 1600 km (1000 miles) long and about 75 km (50 miles) in average breadth. The average composition of the entire batholith is tonalitic, and tonalite is, by far, the single most abundant rock type. From one pluton to another, however, the composition ranges from gabbro to granite, and the succession of intrusions is gabbro→ basic tonalite→tonalite→granodiorite→quartz monzonite→granite→ aplite (Larsen, 1948; Jahns, 1954). Isotopic Rb-Sr and U-Pb age determinations, summarized by Krummenacher and others (1975), indicate an emplacement age range on the order of from 135 to 95 m.y., which agrees with the stratigraphic conclusion that most of the granitic rocks were emplaced between Portlandian and Turonian times. The axial part of the batholith is believed to have been emplaced from 155 to 95 m.y. ago and uplifted 80 m.y. ago to shed detritus now present in overlying marine sedimentary strata of Campanian-Mastrichtian age exposed along the northern Baja California coast (Krummenacher and others, 1975).

Eastern Peninsular Ranges Mylonite Zone

A northwest-trending belt of pervasively sheared cataclastic rocks is superposed on the plutonic and pre-batholithic rocks in the Peninsular Ranges just west of the Salton Trough (Fig.12). The San Jacinto and Elsinore faults offset the mylonite dexturally, but the movements within the mylonitic rocks probably ceased long before the beginning of movement on the younger strike-slip faults (Sharp, 1968). The rocks of the mylonite belt range from barely sheared cataclastic augen gneiss to ultramylonite in a zone having a minimum width of 8 km (Sharp, 1979). The mylonite belt and its internal foliation dip moderately E and NE and the lineation, defined by the streaking of dark and light minerals, plunges downdip (Sharp, 1967, 1979).

The depth of burial at the time of metamorphism is estimated to have been from 11 to 23 km at Coyote Mountain; temperatures probably reached from 650° to 700°C (Theodore, 1970). Elsewhere exposures of the belt are probably shallower by 3 to 6 km (Sharp, 1979).

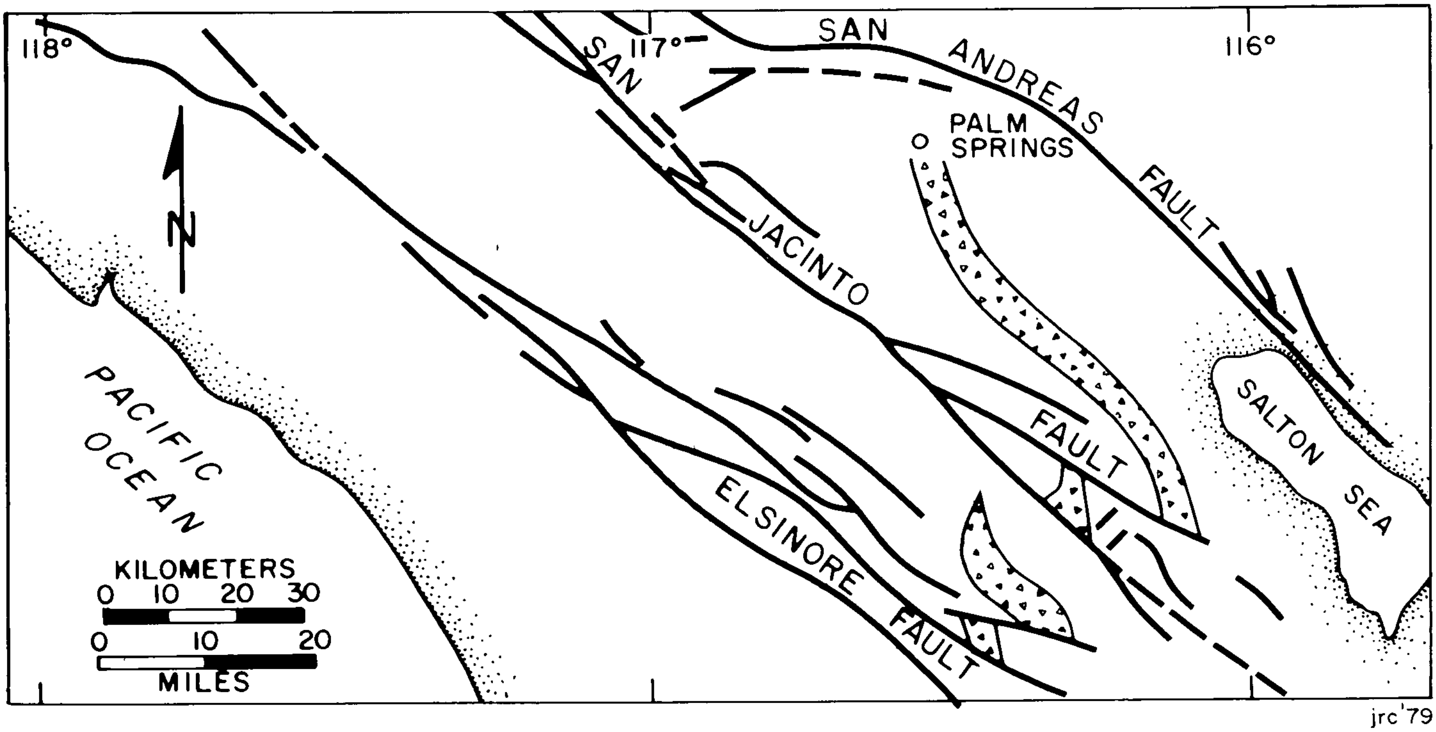


Fig. 12. Locality map of the Santa Rosa mylonite belt showing right separation by fault strands of the San Jacinto and Elsinore fault zones. Redrawn after Theodore (1966).

Thus considerable erosion has taken place since the deformation ceased.

The age of the mylonitic deformation is considered to be Late Cretaceous or Paleocene in age, because the cataclasites are overlain uncomformably by Eocene conglomerate, whereas mesozonal plutonic rocks of the Southern California batholith are affected by the deformation (Sharp, 1967, 1979; Theodore, 1966).

Post-batholithic Rocks

As much as 1200 m (4000 ft) of arenaceous marine strata of Paleocene and Eocene age and about 900 m (3000 ft) of nonmarine strata of Oligocene (?) and Early Miocene age rest on a widespread erosional surface of low relief in the Santa Ana Mountains and western Peninsular Ranges. These rocks are described elsewhere and are subjects of other field trips in this series, so they are not considered further here.

RANGES ALONG THE NORTHEAST EDGE OF THE SALTON TROUGH

The mountains along the northeast margin of Salton Trough are underlain by a variety of Precambrian and Mesozoic metamorphic and plutonic rocks that have been intruded by granitic plutonic and hypabyssal rocks in both Mesozoic and Cenozoic times.

Orocopia Mountains and Mecca Hills

Basement rocks in the Orocopia Mountains and in their satellitic Mecca Hills on the west comprise a complex of Precambrian gneiss and migmatite intruded by anorthosite, syenite and related rocks that, in turn, are intruded by Mesozoic granitoids and Mid-Tertiary calc-alkaline volcanic epizonal plutonic rocks. The complex of Pre-Tertiary rocks tectonically overlies the Orocopia Schist, a metasedimentary unit, the metamorphism of which is believed to have taken place soon after its deposition in Late Mesozoic time (Ehlig, 1968, Dillon and Haxel, 1978; Crowell, 1979).

The gneiss consists of mafic meta-igneous gneiss, banded and laminated paragneisses, amphibolite and migmatite, all of which are intruded by anorthosite, syenite and related rocks including gabbro, diorite and leucodiorite locally intruded by pre-Phanerozoic granite, now augen gneiss (Dillon, 1975). Field relationships show the following intrusion sequence: mafic dikes → mafic segregations → anorthosite → leucodiorite → gabbro → porphyritic granite (augen gneiss) → diorite → syenite. The U-Pb isotopic ages of the gneiss, migmatite and syenite are 1670, 1475, and 1225 m.y., respectively (Silver, 1971). All of these rocks have been metamorphosed to the amphibolite facies of regional metamorphism.

Crowell and Walker (1962) showed that the unusual petrology and intrusion sequence of these rocks in the Orocopia Mountains correspond with basement rocks in the western San Gabriel Mountains more than 300 km to the northwest and on the other (southwest) side of the San Andreas fault. Thus, it was this correlation which led Crowell (1960; 1962) to suggest the great magnitude of strike-slip on the southern part of the San Andreas fault.

Light-colored granitoids of Mesozoic age intrude the Precambrian basement complex but not the Orocopia Schist in the Orocopia Mountains as well as in the Little San Bernardino, Cottonwood and Hayfield Mountains that bound the northeastern end of Salton Trough. The most common rock type is fine- to medium-grained leuco-quartz monzonite having complicated migmatic borders. These rocks have yielded K-Ar ages from 71 to 88 m.y. (Armstrong and Suppe, 1973), and are more related compositionally to the Sierra Nevada batholith than to the Southern California batholith.

The core of the Orocopia Mountains is made up of dark gray Orocopia Schist consisting of quartzo-feldspathic schist, mica schist, albite amphibolite, quartzite and rare marble and serpentine, all of which are metamorphosed to greenschist-facies grade. Their protoliths comprised siltstone, shale and basalt associated locally with deepwater (?) limestone, ferruginous/manganiferous chert, and pods of ultramafic rock. The Orocopia Schist is lithologically and temporally similar to the Pelona and Rand schist to the north and to the Julian schist in the Peninsular Range (Ehlig, 1968).

The thickness of the Orocopia Schist is unknown because its base is not exposed. Most writers currently regard the schist as Late Mesozoic in age because it has been overthrust in Late Cretaceous or Paleocene time by the Precambrian complex described above and is not intruded by Mesozoic granitoids which are otherwise so prevalent in pre-Tertiary rocks in southern California.

The Orocopia Schist is isoclinally folded, is strongly foliated, and is exposed as fensters within the Orocopia and Chocolate Mountains. In this regard, nearly every other body of schist in southern California which is thought to be correlative with the Orocopia Schist is also tectonically overlain by high grade Precambrian and other metamorphic rocks. In fact, Crowell (1974c) and Dillon and Haxel (1978) postulated that all the thrust sheets are tectonically related as parts of a major regional allochthon known as the Vincent-Chocolate Mountains thrust whose principal displacement took place in Late Mesozoic-Early Cenozoic time (Ehlig, 1968). In the Chocolate Mountains, the thrust is a folded, gently to moderately northeast-dipping fault surface with cataclastic gneiss above and mineralized Orocopia Schist below the surface. Elsewhere, the thrust contact is marked by a zone of mylonite.

About 1500 m (4800 ft) of Early and Middle Eocene marine strata nonconformably overlie granitic basement in the northeastern Orocopia Mountains (Crowell and Susuki, 1959; Crowell, 1975b). Called the Maniobra Formation, these strata comprise interbedded siltstone, sandstone, some sandy limestone, breccia and massive conglomerate with large, polished boulders up to 10 m in diameter. They are interpreted as laid down at the eastern edge of a fore-arc basin, later displaced by San Andreas movement (Crowell, in press). The Eocene strata are overlain unconformably by the Diligencia Formation, which comprises about 1500 m (5000 ft) of volcanic and nonmarine clastic rocks of Early Miocene and perhaps Oligocene age, based on a single vertebrate fossil find (Crowell, 1975b). K-Ar isotopic ages on interlayered volcanic rocks range from 18.6 ± 1.9 m.y. (Spittler, 1974) to 22.4 ± 2.9 m.y. (Crowell, 1973). Neither the Maniobra nor the Diligencia Formations, nor rocks equivalent in age and lithology, have been found elsewhere in the Salton Trough, but have probable correlatives in the central Transverse Ranges from 220 to 280 km (135 to 175 miles) to the northwest across the San Andreas fault (Crowell, 1975b).

Dikes, ranging in composition from pyroxene andesite to sanidine rhyolite, locally intrude pre-Tertiary basement in the Mecca Hills and Orocopia Mountains. These dikes are part of a terrane of Oligocene volcanism which is more extensively developed farther southeast in the Chocolate Mountains and in western Arizona (Crowe, 1978) and which is outlined in more detail by Korsch (Chap. 9, this volume).

CHOCOLATE AND CARGO MUCHACHO MOUNTAINS

The Chocolate Mountains have not been studied extensively because they are within an active bombing range. They and adjacent ranges to the east contain widespread Cenozoic volcanic and volcaniclastic rocks that overlie pre-Cenozoic basement rocks (Crowe, 1973a, 1978; Korsch, Chap. 9, this volume). The basement rocks are largely of the kind and type which are found in the Orocopia Mountains (Dillon, 1975; Haxel and Dillon, 1978) and also include: (1) porphyritic granodiorite which is lithologically and temporally identical to the Lowe Granodiorite in the central San Gabriel Mountains, and (2) exhumed domes of a distinctive rapakivi-texture quartz latite porphyry in Salton Creek Wash between the Orocopia and Chocolate Mountains. Dikes of this rock are also present in the Mecca Hills.

The granodiorite, which has been found at the north and south ends of the Chocolate Mountains (Crowell, 1975a; Dillon, 1975), is medium- to coarse-grained and faintly foliated with characteristic large orthoclase phenocrysts, smaller and irregularly distributed hornblende phenocrysts, and less than 10% quartz. Crowell (1975a) has tentatively correlated the granodiorite with the Lowe Granodiorite in the central San Gabriel Mountains where Silver (1971) obtained an isotopic age of 220 m.y. (earliest Triassic) on the rock. The Lowe Granodiorite is one of the most distinctive plutonic rocks in southern California. Similar rocks in the Chocolate Mountains are also almost certainly Lowe Granodiorite (Dillon, 1975) and, as such, are another bit of strong evidence for large-scale strike slip on the San Andreas fault.

The quartz latite porphyry in Salton Wash and the Mecca Hills also provides support for great strike slip on the San Andreas fault. Lava flows, tuff, and stream-transported detritus of this distinctive rock have been found in Soledad Basin in the central Transverse Ranges (Ehlig and Ehlert, 1972) about 300 km northwest of Salton Wash and on the southwest side of the San Andreas fault.

The Cargo Muchacho Mountains, composed largely of amphibolite metamorphic rocks intruded by mesozonal plutonic rocks (Haxel and Dillon, 1973), expose two rock units of particular petrologic and tectonic interest. The first unit, kyanite-bearing and dumortierite-bearing muscovite schist, because of the distinctive mineralogy,ought to be unique "tectonic tracers" for the San Andreas fault, just as other distinctive rocks of the Orocopia and Chocolate Mountains are for documentation of slip on major faults in the Salton Trough. Clasts of kyanite-bearing schist have been found in the Coachella Fanglomerate in Whitewater Canyon west of the San Andreas fault.

The other rock unit is a distinctive porphyritic quartz monzonite, the so-called "Peterson porphyry," informally named for Martin Peterson who found clasts of the rock together with equally distinctive clasts of magnetite in the Coachella Fanglomerate, 215 km to the northwest at the northwest end of Salton Trough on the southwest side of the San Andreas fault (Peterson, 1975). These two rocks crop out in the Cargo Muchacho Mountains and are probably the bedrock source for the Coachella Fanglomerate (Peterson, 1975). Interbedded andesite flows in the Coachella Fanglomerate give a K-Ar age of 10.0 ± 1.2 m.y.

SUMMARY

A wide variety of lithologically and temporally diverse crystalline and sedimentary rocks are found in the mountains surrounding Salton Basin and can be extrapolated beneath Late Cenozoic sediments around the margin of the basin. The exact nature of the rocks beneath any given part of the Salton Trough is largely a matter of speculation, however, for two reasons. First, if the interpretation is tenable that the Salton Trough is the landward extension of a spreading plate boundary as summarized and discussed by Crowell and Terres (Chap. 2, this volume), then young mantle-derived igneous rocks should be welling up and healing the rift in the floor of Salton Trough. Except perhaps for a few of the young volcanic rocks which crop out locally around the edge of the trough and in small volcanic fields in the center of the trough (Korsch, Chap. 9, this volume), the nature and extent of the new floor of Salton Trough are subjects for geophysical and geological interpretation. Second, the lithologic diversity is readily apparent from the material presented in this paper and from inspection of any reasonably detailed geologic map of the region: clearly the areal scale of domains consisting of a single rock type is quite small in relation to the area of the trough.

Quite apart from studying the basement rocks of the surrounding mountains to infer the nature of the Salton Trough fundament, however, is the role unique rock types and rock assemblages play as "tectonic tracers" to document fault separation and slip. Several examples are given in the text of this summary paper that bear both on the magnitude and the timing of slip on the San Andreas fault. Whereas the technique and conclusions outlined here are not new (Crowell, 1962), they still illustrate the role and the necessity of thorough geologic and petrologic studies of ancient rocks for unraveling recent tectonic problems and promoting synthesis. The relative lack of displacement information for faults west of Salton Trough is due, in part, to the lack of just this kind of information. Sharp's (1967) study of the basement rocks along part of the San Jacinto fault is a noteworthy exception, but much more detailed mapping and routine petrologic work are needed for that and other faults, especially the Elsinore fault (Crowell and Ramirez, Chap. 3, this volume).

Chapter 8

GEOLOGY OF THE NORTHEAST BORDER OF THE SAN JACINTO PLUTON, PALM SPRINGS, CALIFORNIA

by

Robert Sydnor
Engineering Geologist
V.T.N. Corp.
Box 6-19529
Irvine, CA 92713

ABSTRACT

Intrusive relations along the northeast border of the San Jacinto pluton are well exposed in the 3-km high declevity adjacent to the Palm Springs Tramway. Here predominating granodiorite of the pluton is intermixed with tonalite, diorite, gabbro, and lesser amounts of other rocks. These mixed rocks constitute a felsic-mafic complex and several types of dikes and bodies are recognizable. Mafic magma, containing much heat, appears to have invaded a granodiorite mush so that both syn-granitic and post-granitic dikes formed.

INTRODUCTION AND REGIONAL SETTING

The San Jacinto pluton, exposed over 650 km^2, is roughly bounded by the San Jacinto fault on the west and southwest, San Gorgonio Pass on the north, and the Santa Rosa mylonite belt on the east (Fig.13). It is located in the northeastern part of the southern California batholith within the Peninsular Ranges and is believed to be Late Cretaceous in age.

The total relief is over three vertical kilometers in the study area, rising from near sea level at Palm Springs to the summit of Mt. San Jacinto at an elevation of 3,292 m.

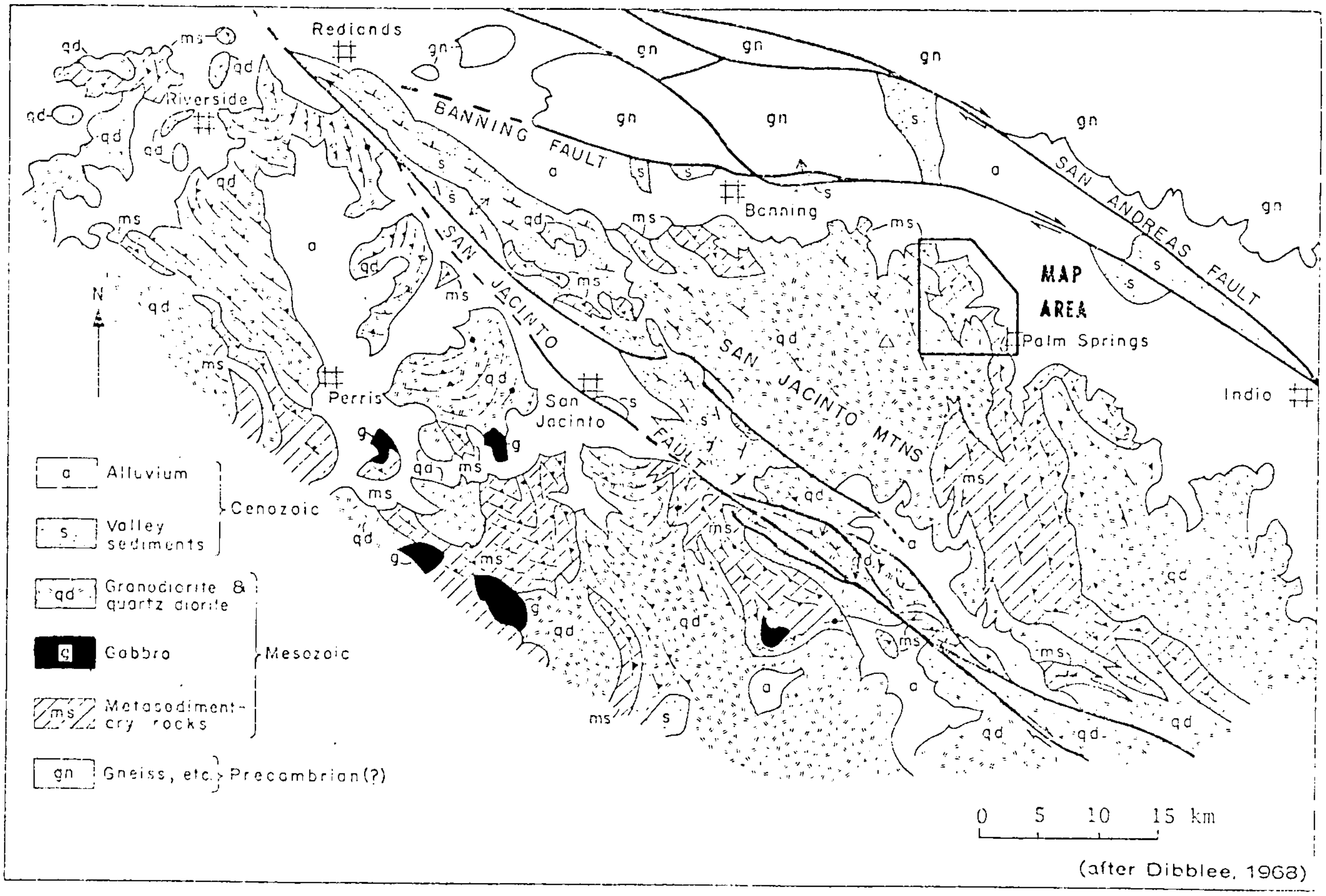


Fig. 13. Regional geologic map of the San Jacinto Mountains showing location of Palm Springs Aerial Tramway map area in San Jacinto pluton.

Batholithic Rocks

Granodiorite is the most widespread rock unit of the San Jacinto pluton. Tonalite, diorite, and a small amount of gabbro are exposed in the outer parts of the pluton. One small stock of olivine norite is partially exposed near the second tramway tower. Hornblende diorite is the most common mafic rock in the Chino Canyon area and is definitely older than the hybrid (?) tonalite as shown by numerous xenoliths of diorite in the tonalite; however, the diorite and the granodiorite have inter-penetrating dikes with enigmatic age relationships.

Metamorphic Rocks

Metamorphic country rocks are exposed in the lower and middle parts of Chino Canyon, visible from the tramway road. They consist of recrystallized limestone, calc-silicate schist, quartz-mica schist, and flaser gneiss. These older metamorphic country rocks are strongly foliated, folded in places, and were evidently subjected to several periods of forcible granitic intrusion and regional tectonism. The schematic geologic cross section (Fig.14) through the axis of Chino Canyon indicates the structural relationship of the metamorphic rocks with the batholithic rocks and the location of the felsic-mafic dike complex.

Age of the Pluton

Radiometric age dates are not available for the Palm Springs/ Chino Canyon area, but K/Ar dates determined by Armstrong and Suppe (1973) for the SW part of the pluton yield an isotopic age of 84 m.y. Recent oxygen isotope studies by Taylor and Silver (1978) give a preliminary indication that the San Jacinto-Santa Rosa block is geochemically different from other plutons in the southern California batholith. It is lower in the ^{18}O and higher in $^{87}Sr/^{86}Sr$ than tonalite and granodiorite from plutons across the San Jacinto fault to the south and west.

Dikes

There are four kinds of dikes in the Chino Canyon complex:

(1) Homogeneous dikes (very common)

- (a) Pegmatites (although many are internally zoned)
- (b) Fine-grained diorite and tonalite dikes
- (c) Hornblende lamprophyre dikes (which may be composite)
- (d) Coarse-grained granodiorite dikes

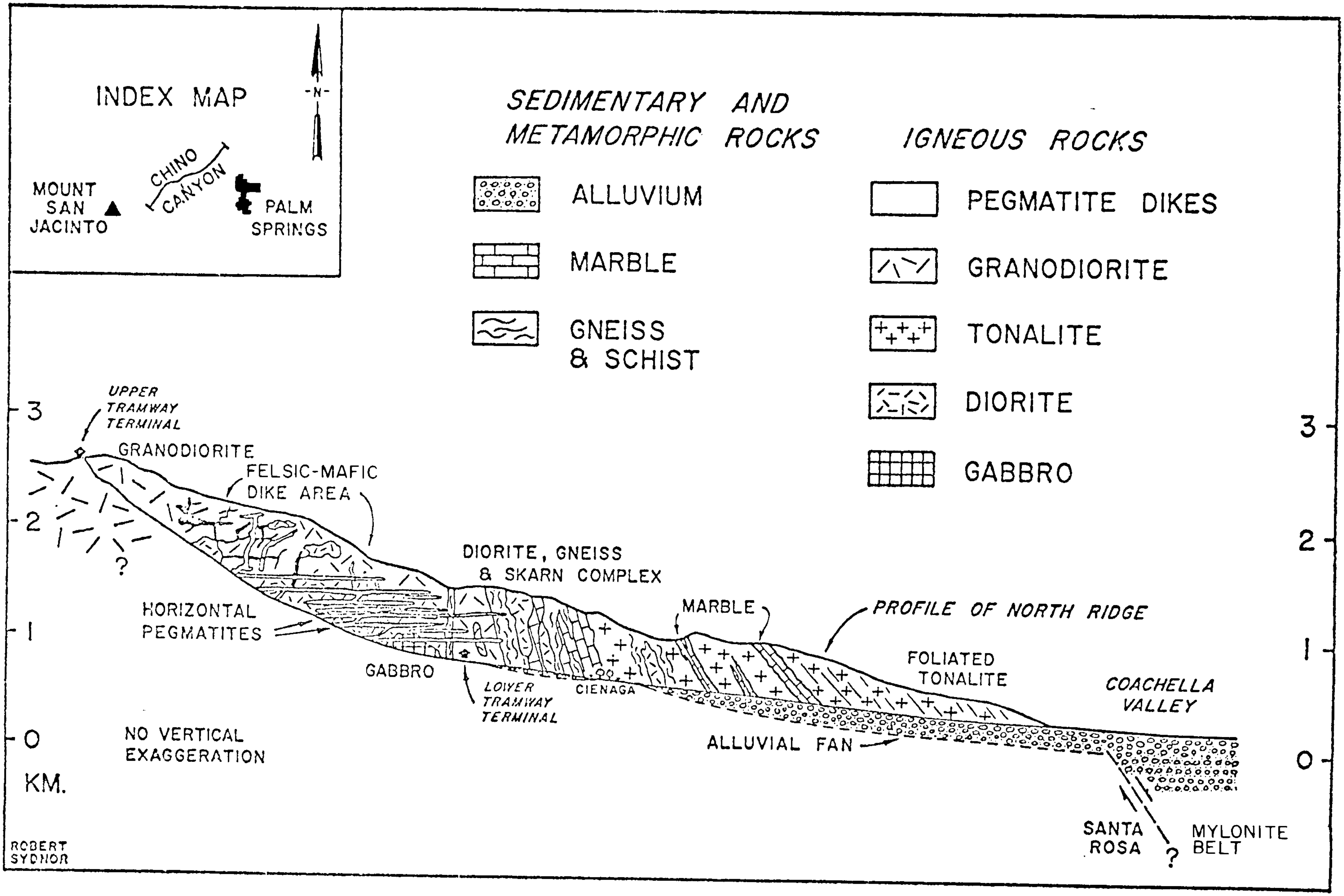


Fig. 14. Schematic cross section of Chino Canyon.

(2) Composite dikes (less common)

   (a) Coarse-grained pegmatite dikes and fine-grained granodiorite dikes
   (b) Hornblende lamprophyre dikes with hybrid (?) diorite borders
   (c) Pegmatite and hornblende lamprophyre dikes
   (d) Compositionally-layered dikes

(3) Rheomorphic dikes, remobilized by palingenesis (somewhat rare)

(4) Irregular structures (rare and unusual)

   (a) Proto-orbicular structures
   (b) Felsic septa or apophyses associated with rheomorphic dikes

The homogeneous dikes are the most abundant variety; they were studied to determine relative age relationships. The large white pegmatites which are easily viewed from the tramway are evidently the youngest rock unit; they cross-cut and intrude all other rock units. Quite likely the pegmatites represent the low-melting residual liquid and aqueous gas fraction of the granodiorite magma. The emplacement of a great volume of pegmatite fluid was probably associated with the fracturing of the net-veined dike complex; large pegmatite dike swarms are absent elsewhere in the San Jacinto pluton.

Although rheomorphic dikes are rarely exposed, they give a valuable insight into the classic question of metasomatism versus magmatism and may reveal the presence of co-existing magmas.

Intermingling of Felsic-Mafic Magmas

Based upon both field and laboratory study, it appears that the dike complex within Chino Canyon was formed by ortho-magmatic and rheomorphic processes rather than metasomatism or granitization. It also appears that the net-veined complex and rheomorphic dikes may be related to a gradational and morphological series, postulated by other workers (notably the British school of petrologists). This gradational relationship appears to depend on two main factors:

(1) the relative volume of mafic magma intruded, and therefore the amount of heat introduced; and

(2) The degree of consolidation of the felsic host, or the ratio of crystals to melt.

The volume of the mafic magma introduced into a felsic-mafic complex will directly affect the amount of heat available to remobilize the felsic host rock (Fig. 15). Large volumes of mafic magma will promote a large net-veined complex, while small amounts of mafic magma may lead to only a slight intermingling with the felsic host rock. In each case, the felsic host rock is assumed to be a crystal mush, the mafic intrusion is assumed to be mobile, but the relative volume of the mafic intrusion changes. All three examples are recognized in Chino Canyon, particularly the net-veined complex and interfingering apophyses; dikes with discrete pillows are less common. The small apophyses (on a scale of a few tens of centimeters) are farther from the masses of olivine norite and hornblende diorite, whereas the net-veined complexes appear to be spatially closer to the mafic intrusions.

The time of mafic dike intrusion seems to be an equally important factor for dike morphology. Mafic dikes have a variable shape depending upon whether they intrude a felsic magma above its liquidus (pre-granitic dike), during its crystallization (syn-granitic dike), or after the felsic magma has completely crystallized to a solid rock (post-granitic dike). Criteria for the evaluation of these three periods include the presence or absence of the following features:

(1) interfingering apophyses or back-veining

(2) chilled borders

(3) high-temperature minerals not in equilibrium with the granitic host

(4) overall morphology of the dike

These relationships are summarized in Fig. 16. In the Chino Canyon dike complex, some syn-granitic and many post-granitic dikes are recognized. A summary of the geologic history is given in Table 1.

Economic Geology

No significant mineral resources are known in the Chino Canyon area. The recrystallized limestone just west of Windy Point was investigated just after World War II as a possible quarry for portland cement, but the City of Palm Springs annexed this area to protect the "resort image" of the city. Because very strong winds blow through San Gorgonio Pass on a regular basis, it is possible that Windy Point could become a suitable windmill site to generate electric power for local communities.

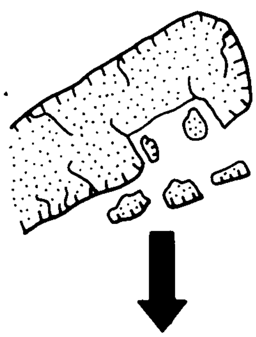
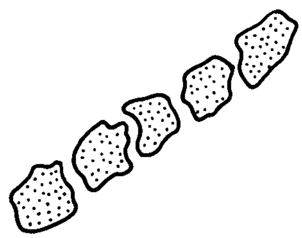
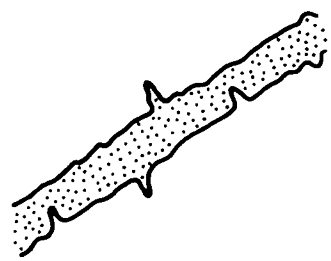
→ DECREASING VOLUME OF MAFIC MAGMA →			
STATE OF FELSIC HOST	CRYSTAL MUSH	CRYSTAL MUSH	CRYSTAL MUSH
STATE OF MAFIC INTRUSION	MOBILE MAGMA	MOBILE MAGMA	MOBILE MAGMA
VOLUME OF MAFIC INTRUSION	10^7 M^3	10^4 M^3	10^3 M^3
RESULTS	 SINKING BLOCKS	 MAFIC DIKE WITH FINE-GRAINED MARGINS	 INTERFINGERING APOPHYSES

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Fig. 15. Diagrammatic interpretation of the form of mafic dikes, depending on the available heat to remobilize the felsic host rock. The amount of available heat depends on the volume of the mafic dike.

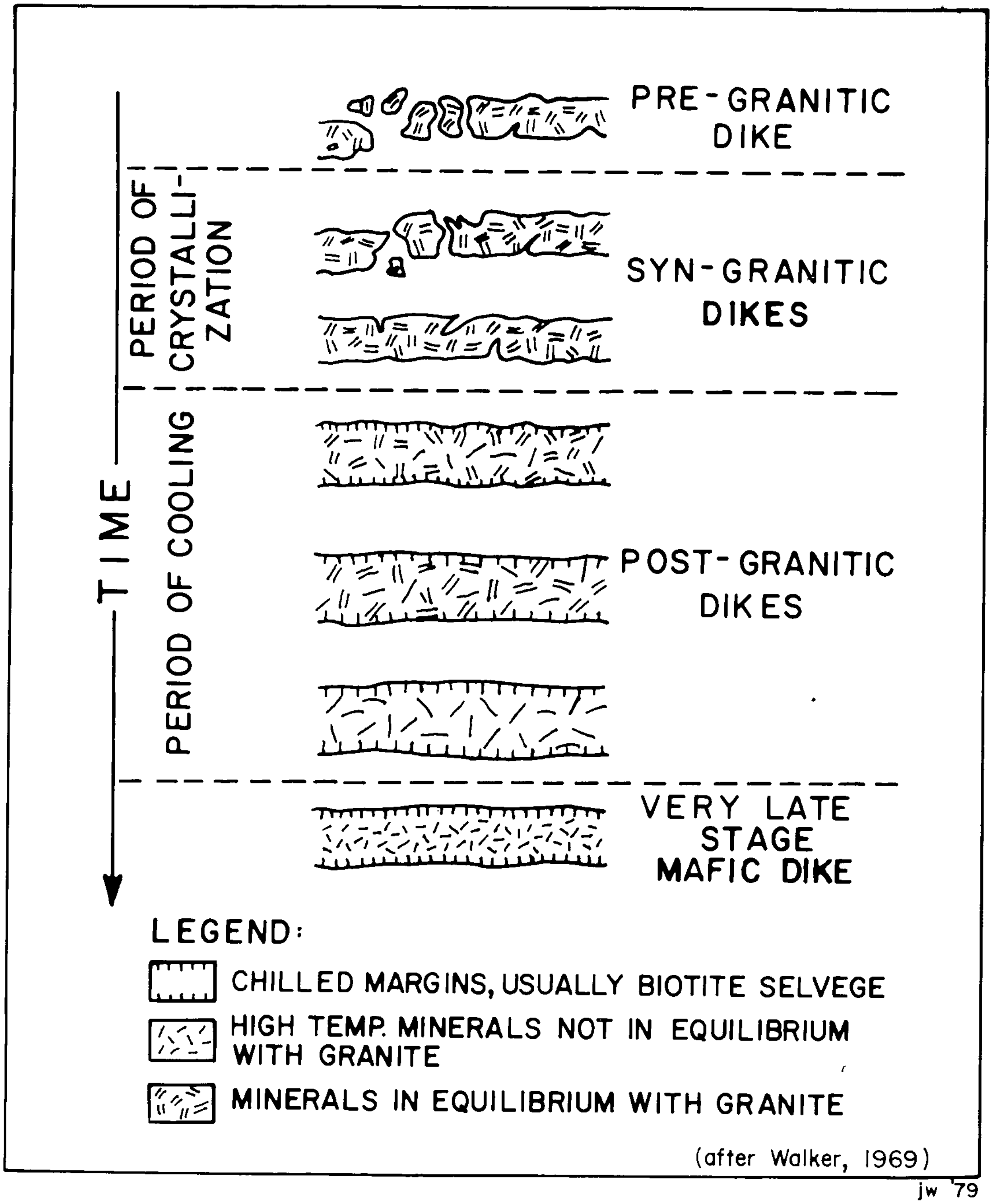

Fig. 16. Diagram illustrating how the form and character of mafic dikes in granite depend on the time of dike intrusion.

Quaternary	Unroofing and uplift of the San Jacinto block. Development of incised canyons and very steep alluvial fans. Possible minor glaciation near the summit of Mount San Jacinto during the Wisconsin Stage. Active faulting of the San Andreas fault system.
Tertiary	Major displacement on the San Andreas fault system. Active right-lateral faulting on the Santa Rosa mylonite belt. Foliation of the border rocks of the pluton on the northeast side. Beginning of uplift of the San Jacinto block in Late Tertiary time.
Late Cretaceous	Several periods of plutonism: (1) Gabbro and diorite emplaced first. (2) Granodiorite emplaced, causing (3). (3) Hybrid (?) tonalite from reaction with older mafic units (1). Concurrent metamorphism of sedimentary country rocks. Coexisting felsic and mafic magmas in Chino Canyon area. (4) Development of lamprophyric dikes within the felsic-mafic rock complex. (5) Late-stage granitic pegmatites emplaced locally within the felsic-mafic rock complex.
Pre-Cretaceous (Late Mesozoic ?)	Deposition of sediments in a shallow marine milieu. Subsequent lithification. Uncertain regional metamorphism.

Table 1. Summary of the geologic history of the northeast border of the San Jacinto pluton.

Chapter 9

CENOZOIC VOLCANIC ACTIVITY IN THE SALTON TROUGH REGION

by

R. J. Korsch*
Department of Geological Sciences
University of California
Santa Barbara, CA 93106

ABSTRACT

Cenozoic volcanic rocks in the vicinity of the Salton Trough region are part of a Cenozoic volcanic province which covers much of western North America. In southernmost California the volcanic rocks have been subdivided into two discrete groups based on their geographic distribution, isotopic ages and tectonic setting. Volcanic rocks belonging to both groups are east of the present-day San Andreas fault in the Chocolate Mountains. Here the predominant group has isotopic ages from 25 m.y. and 22 m.y. and a chemistry similar to the widespread calc-alkaline and alkaline volcanic suites of the Basin and Range Province. They are interpreted as part of a continental margin magmatic arc system which was genetically related to a Cenozoic subduction zone located farther west.

The younger volcanic rocks (22 m.y. - 13 m.y.) east of the San Andreas fault and the volcanic rocks now found west of the San Andreas fault are mainly basaltic in composition and represent a major change in the type of volcanism which occurred at about 22 m.y. These volcanic rocks are a product of magmatism related to crustal extension which initially produced volcanic rocks associated with continental rifting of basin-and-range type. This type of crustal extension was the forerunner to the development of basins possibly floored with oceanic crust. The very young (16,000 years) bimodal basaltic-rhyolitic volcanic rocks which form the Salton Buttes at the south end of the Salton Sea lie above an inferred spreading center at depth.

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*Permanent address: Armidale College of Advanced Education
Armidale, N.S.W., 2350
AUSTRALIA

INTRODUCTION

Cenozoic volcanic rocks in the vicinity of the Salton Trough are part of much larger volcanic fields distributed over much of western North America. The evolution of these volcanic rocks in the western United States has been studied by many workers, and regional syntheses have been written by McKee (1971), Noble (1972, Lipman, Prostka, and Christiansen (1972), Christiansen and Lipman (1972), Snyder, Dickinson, and Silberman (1976), Cross and Pilger (1978) and Gastil, Krummenacher and Minch (1979), among others. Apart from a discussion of the tectonic setting, this description of the volcanic rocks concerns only those in the vicinity of the Salton Trough, and those near the route which the field trip will follow.

The volcanic rocks fall into two discrete groups based in combination on their geographical distribution (Fig. 17), isotopic ages (Fig. 18), and tectonic setting (Fig. 19): (1) Early-Mid Cenozoic volcanic rocks in the Chocolate Mountains east of the present-day San Andreas fault; and (2) Mid-Late Cenozoic volcanic rocks west of the San Andreas fault in the Salton Trough area, and in the Peninsular Ranges.

Latest Pleistocene or Holocene volcanic domes lie along the southern margin of the Salton Sea. These rocks are discussed separately because of their very young age and tectonic implications.

Approximately 300 km of offset has been documented on the San Andreas fault since Late Miocene time (Crowell, 1960, 1962, 1979). Early Cenozoic volcanic rocks of types found E of the Salton Trough have not been recorded west of the San Andreas fault, but displaced approximately 300 km to the northwest. Even though the volcanic rocks of the Chocolate Mountains and adjoining areas have not been discovered as offset by movement on the San Andreas fault, they provided significant sources for detritus in Cenozoic sediments which have been moved tectonically great distances relatively to the northwest. Some Cenozoic volcanic rocks are so distinctive that they have been used to reconstruct past movement histories of the San Andreas fault (Crowell, 1962; Ehlig, Ehlert, and Crowe, 1975; Peterson, 1975; Matthews, 1976). By corollary, Miocene volcanic rocks now lying west of the San Andreas fault in the Salton Trough region were probably emplaced up to 300 km to the south of their present position.

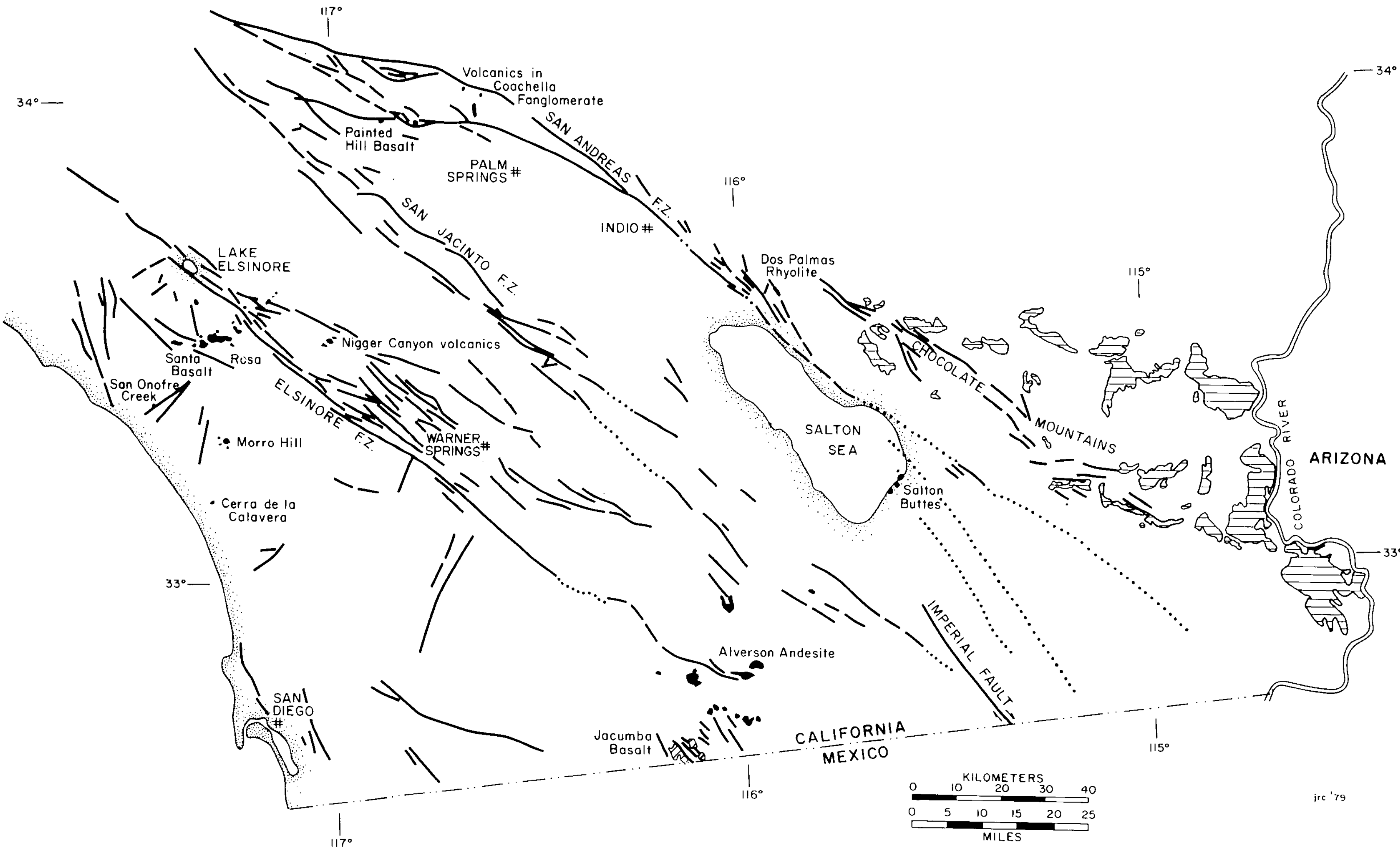

Fig. 17. Distribution of Cenozoic volcanic rocks in southernmost California. Volcanic rocks west of the San Andreas fault are shown in solid black, with the exception of the Jacumba Basalt (diagonal lines). Volcanic rocks east of the San Andreas fault are shown in horizontal lines, with the exception of the Dos Palmas Rhyolite (solid black).

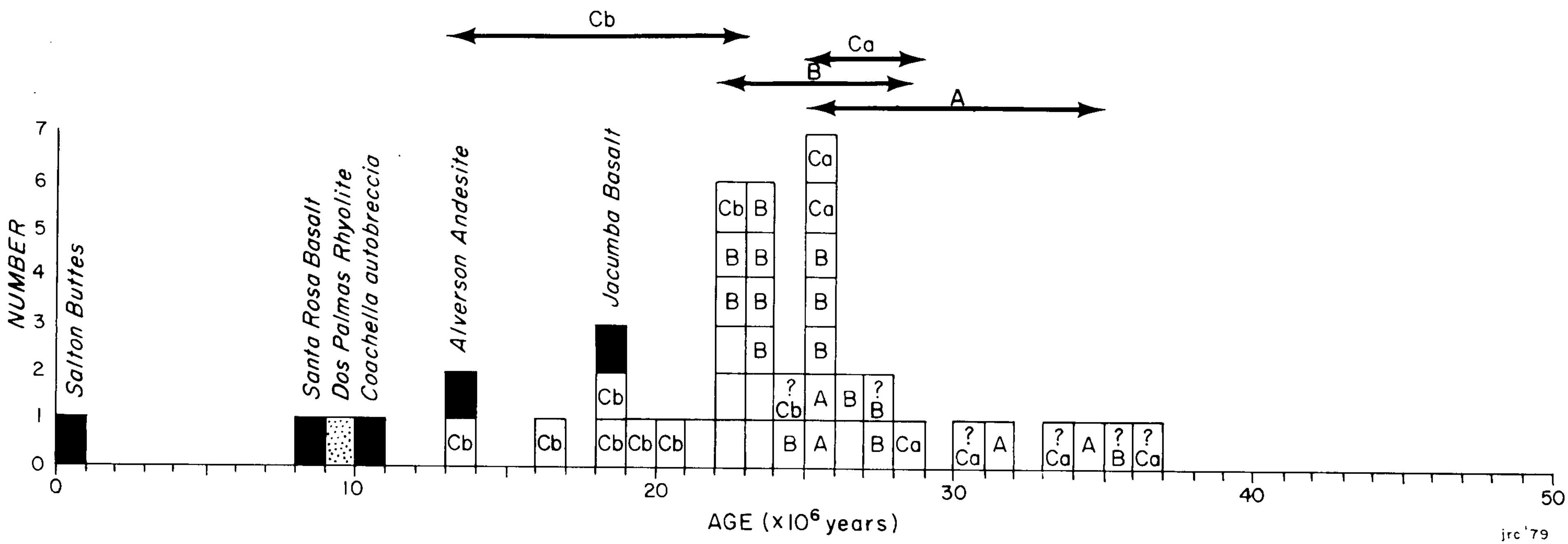

Fig. 18. Distribution of isotopic (K-Ar) ages from volcanic and plutonic rocks in southernmost California. Ages, from volcanic rocks west of the San Andreas fault, are shown in solid black, and those from east of the San Andreas fault are blank. Ages from plutonic rocks east of the San Andreas are indicated by diagonal lines. Letters A, B, C_a and C_b refer to volcanic units recognized by Crowe and others (1979) and a question mark (?) denotes an age which, on field evidence, is probably spurious. Data taken from Hawkins (1970), Crowell (1973), Olmsted and others (1973), Spittler (1974), Sylvester and Smith (1976), Miller and Morton (1977), Crowe (1979), and Crowe and others (1979).

EARLY-MID CENOZOIC VOLCANIC ROCKS OF THE CHOCOLATE MOUNTAINS

The major input to the geology of the Chocolate Mountains and nearby areas east of the present-day San Andreas fault in southeastern California has been by J. C. Crowell and his students (Crowell, 1962, 1975; Crowe, 1973, 1978; Crowe, Crowell and Krummenacher, 1979; Haxel and Dillon, 1973). The Cenozoic volcanic rocks of this area (Fig. 17) are part of a much larger volcanic field in southern California in the Mojave Desert south of the Garlock fault and east of the San Andreas fault. One notable exception is the conspicuous absence of Cenozoic volcanic rocks from the eastern Transverse Ranges immediately northwest of the Chocolate Mountains area.

Detailed work by Crowe (1978) on a complex series of Oligocene volcanic rocks in the Picacho area of the southernmost Chocolate Mountains has been complemented by a study of the volcanic rocks over a much larger region (Crowe, Crowell, and Krummenacher, 1979). A tripartite volcanic stratigraphy was developed with general application over the whole of the Chocolate Mountains. Crowe, Crowell and Krummenacher (1979) recognized that rocks at widely separated volcanic centers could be divided into three major sequences in which the stratigraphic positions of the major volcanic rock units are consistent. It must be stressed, however, that there are significant regional variations in ages and eruptive histories of the individual volcanic centers.

The basal unit (A) consists of basaltic to rhyodacitic lava flows, flow breccia, laharic breccia and associated plugs. These rest unconformably on pre-Cenozoic basement, and locally overlie and interfinger with fanglomerate. The unit is intruded by comagmatic plutonic rocks (Miller and Morton, 1977) ranging from granodiorite and quartz monzonite to porphyritic granite, and Crowe, Crowell and Krummenacher (1979) recognized at least two intrusive phases. Porphyritic granite intrudes slightly more mafic granitic rocks, and at Mt. Barrow (central Chocolate Mountains), a granitic stock is cross cut by a northwest-trending dike swarm that locally also intrudes the silicic volcanic unit (B).

The middle unit (B), termed the silicic volcanic unit by Crowe, Crowell and Krummenacher (1979), consists of rhyodacite to rhyolitic lava flows, domes and associated pyroclastic and volcaniclastic rocks. Included in this unit is a welded to unwelded rhyolite ignimbrite which is a major ash flow sheet mapped discontinuously for a distance of over 35 km (see Figure 3 of Crowe, 1978). It has a K-Ar age of 26.2 m.y. ± 1.6 m.y. (Olmsted, Loeltz, and Irelan, 1973). The rocks of Unit B overlie rocks of Unit A, locally with a slight angular discordance. The Cenozoic plutons usually do not intrude Unit B.

The capping volcanic unit (C) consists of lava flows of pyroxene dacite to olivine basalt and forms conspicuous capping lava flows. Locally they are interbedded with, and overlie fanglomerate. Crowe, Crowell and Krummenacher (1979) used K-Ar ages and chemistry to distinguish two subunits: C_a overlaps in age with the silicic volcanic unit (B), whereas C_b is separated by a distinct age gap from Unit B. Also, Unit C_b was erupted from vents largely unrelated to the volcanic centers of Units A, B, and C_a and thus could be elevated to unit status, because C_b represents a transition to more basaltic volcanism.

K-Ar isotopic ages for the units were determined by Crowe, Crowell and Krummenacher (1979) as: Unit A - 26 m.y. to 35 m.y.; Unit B - 22 m.y. to 28 m.y.; Unit C_a - 25 m.y. to 29 m.y.; Unit C_b - 13 m.y. to 22 m.y. Plutonic rocks associated with Unit A have K-Ar ages from 21 m.y. to 26 m.y., which are younger than parts of Units B and C_a despite the regional stratigraphic disconformity between Units A and B. Possible reasons for this contradiction are that the plutonic ages are minimum ages caused by regional thermal effects of prolonged plutonism and volcanism, or that the volcanism of Unit B maintained the thermal gradient above the closure temperature of minerals such as plagioclase, sanidine, hornblende, or biotite which were used for dating.

In the Picacho area, Crowe (1978) showed that the volcanic rocks of Units A, B and C_a are similar in their major chemistry to the widespread Cenozoic calc-alkaline and alkaline volcanic suites of the Basin and Range Province. The olivine basalt of Unit C_b is an olivine tholeiite in composition.

VOLCANIC ROCKS IN THE SALTON TROUGH AND PENINSULAR RANGES

Jacumba Basalt

The Jacumba Basalt (Dibblee, 1954) is localized near traces of faults which are possible southern extensions of the Elsinore fault zone. A volcanic breccia, in which a major component is basalt, is overlain by lava flows of basalt, basaltic andesite and andesite. The basalt flows have vesicular to scoriaceous bases and tops, and pahoehoe surfaces are common. In the thicker flows, the interiors are massive and a crude columnar jointing has developed. The basalts are high-alumina basalts with tholeiitic affinities, and the basaltic andesites and andesites, which make up only about 10% of the present outcrops, are considered by Hawkins (1970) to be late-stage differentiation products of the basalt. Hawkins (1970) obtained a K-Ar age of 18.7 ± 1.3 m.y. for a lower flow in the series.

Alverson Andesite

The Alverson Andesite (Fig. 17) is a dark mauve to gray, plagioclase-hornblende andesite in the southwest part of Imperial Valley (Dibblee, 1954). The lavas are interbedded with gray andesite tuff. Their stratigraphic position was re-examined by Woodard (1974), who showed that stratigraphic relationships vary among outcrops. In places lava flows also lie directly on granitic basement, but elsewhere they are separated from the basement by arkosic sandstone and conglomerate of the Anza Formation. The andesite is, in part, a volcanic lithofacies of the Anza Formation, because boulders of the andesite have been found in the upper section of the Anza Formation. K-Ar ages of 13 m.y. and 16 ± 1.0 m.y. for the Alverson Andesite are reported by Sylvester and Smith (1976) and Eberly and Stanley (1978), respectively.

Volcanic Rocks in the San Gorgonio Pass Region

Volcanic rocks are interlayered with the Miocene Coachella Fanglomerate and Pliocene Painted Hill Formation in the San Gorgonio Pass region between the north and south branches of the San Andreas fault (Allen, 1957; Proctor, 1968). A series of pale red and violet volcanic flows of olivine basalt and pyroxene andesite autobreccia 23 m thick is approximately 250 m above the base of the Coachella Fanglomerate (Peterson, 1975). The volcanic rocks wedge out to the south and terminate abruptly to the north near a dike of similar material which may represent the source of the flows. A K-Ar age of 10.0 m.y. ± 1.2 m.y. is given by Peterson (1975) for a pyroxene andesite autobreccia in the sequence.

Flows within the Painted Hill Formation consist of grayish red amygdaloidal olivine basalt and are associated with dikes of olivine basalt (Allen, 1957). These volcanic rocks are probably the youngest in Coachella Valley.

Dos Palmas Rhyolite

The Dos Palmas Rhyolite in the southeastern Mecca Hills rests directly on older crustalline rocks (Dibblee, 1954). It has a K-Ar age of 9 m.y. (Sylvester and Smith, 1976).

Santa Rosa Basalt

The Santa Rosa Basalt consists of a thin series of flows now restricted to mesas northeast and southwest of the Elsinore fault zone in the vicinity of Murietta (Larsen, 1948). The present remnants capping the mesas are 15 m to 125 m thick with individual basalt flows ranging from 1 m to 7 m thick. The flows have been divided into two series by Hawkins (1970) who dated a lower flow at Mesa de Burro and 8.3 m.y. ± 0.5 m.y. The lower flows are massive, columnar-jointed units having a chemical composition of alkali basalt, whereas the upper flows are vesicular to scoriaceous with low-alumina tholeiitic compositions. The close similarity to oceanic tholeiites led Hawkins (1970) to suggest that the basalts were possibly derived from an upward bulge of the mantle in an area of high heat flow.

A 5-m-thick layer of basalt in the Barnard No. 2 oil test well in the Elsinore basin at a depth of 2450 ft (~750 m) has been correlated with the Santa Rosa Basalt (Mann, 1955). This basalt is underlain by conglomerate. It may represent upwelling of mantle material during the formation of the Elsinore pull-apart basin.

Volcanic Rocks in the Peninsular Ranges

Several outcrops of Cenozoic volcanic rocks have been mapped in the Peninsular Ranges by Larsen (1948). The most voluminous is the Santa Rosa Basalt, described above.

At Cerro de la Calavera a dacite stock, crudely circular in outcrop, has contacts which flare outward and upward in a mushroom shape. The stock intrudes both Jurassic plutons and Tertiary sedimentary rocks. It contains inclusions of tonalite, one of which is at least 20 m by 15 m, and which has been partly remelted so that it now has the appearance of obsidian with abundant phenocrysts (Larsen, 1948).

A small volcanic neck of tridymite dacite at Morro Hill intrudes Jurassic granitoids and remnants of Tertiary sedimentary rocks. Nearby are flows and pyroclastic rocks similar to those at Morro Hill. Larsen (1948) noted the unusual character of the lavas and associated stock, and particularly the abundance of tridymite needles which comprise up to 25% of the stock rock. A quartz latite stock near San Onofre Creek cuts granitoids and sedimentary rocks and is similar in composition to the stock at Cerro de la Calavera. The ages of the above stocks and flows are unknown but are inferred to be Tertiary by Larsen (1948).

A cinder cone and associated tuffs, agglomerates, flow breccias and basaltic flows described by Larsen (1948) have been named the Nigger Canyon Volcanics by Mann (1955). Many bombs of scoriaceous basalt up to a few meters in diameter are contained in the agglomerate, and the rocks appear to have been extruded along a series of fractures trending northeast-southwest. They overlie Upper Pliocene or Pleistocene sand and thus Larsen (1948) concluded that they are Quaternary in age. Mann (1955) showed that the cinder cone and associated rocks were produced by at least two periods of eruption along a major transverse fracture which was a structural and physiographic break.

The Salton Buttes: Quaternary Volcanic Domes

Surface volcanic rocks within the Salton Sea Geothermal Field consist of five small rhyolitic domes, collectively called the Salton Buttes, which were extruded onto Quaternary sediments of the Colorado River delta (Kelley and Soske, 1936). These domes lie along a northeast lineament over a distance of approximately 7 km and are spaced 2 to 3 km apart. Muffler and White (1969) obtained a K-Ar age on obsidian from Obsidian Butte of approximately 16,000 years (with a maximum of 55,000 years). Steam is still being discharged from cracks in three volcanoes.

The domes at Red Island are linked by subaqueous pyroclastic deposits, whereas the others are single extrusions with or without marginal lava flows (Robinson, Elders, and Muffler, 1976). As shown by the attitudes of flow foliations on the maps of Robinson, Elders, and Muffler (1976), the domes are mushroom-shaped, and the areally large extent of magnetic anomalies around the entire volcanic field suggests that they are underlain by a relatively large pluton at depth (Meidav and Howard, 1979).

The Salton Buttes consist mainly of rhyolite, locally grading into obsidian. Chemically the rhyolites are low-calcium alkali rhyolites (Robinson, Elders and Muffler, 1976). Xenoliths are abundant at Obsidian Butte and Red Island but rare at Rock Hills, and none has been found at Mullet Island. The xenoliths consist of basalt, granitic rock and sedimentary and metasedimentary rocks. Basaltic xenoliths are the most common, closely followed by granitic xenoliths, whereas sedimentary and metasedimentary fragments are less common (15%, Robinson, Elders, and Muffler, 1976). The basaltic xenoliths chemically are low-potassium tholeiites, and the granitic xenoliths are chiefly sodic granite distinctly different in composition from the enclosing obsidian. The sedimentary and metasedimentary xenoliths were derived from sedimentary fill of the Salton Trough.

Samples of subsurface igneous rocks have been recovered from several wells in the Salton Sea geothermal field and are either fine- to medium-grained silicic rocks or fine-grained to porphyritic basalt. Robinson, Elders, and Muffler (1976) interpret the silicic rocks to be crystallized and altered equivalents of the Salton Buttes rhyolites, and the basalts to be dikes, sills or flows interlayered with very young Salton Trough sediments.

The metasedimentary xenoliths and the subsurface basaltic rocks have been extensively altered. Muffler and White (1969) showed that the Salton Sea area is one of high heat flow, and that changes in mineralogy with depth in wells are related primarily to temperature. Temperatures of up to 360° C are recorded at a depth of 7100 feet (2164 m), and rock in the Salton Sea geothermal system displays a continuous transition from sediments through indurated sedimentary rocks to low-grade metasedimentary rocks of the greenschist facies. The absence of zeolites is noteworthy, because the transition described by Muffler and White (1969) encompasses mineral transformations which are usually considered as diagenetic. The processes are operating at present.

The Quaternary volcanism in the Salton Sea Geothermal Field is characterized by a bimodal rhyolite-basalt association. The fresh basalts, which are found as xenoliths in the rhyolite, are low-potassium tholeiites similar to oceanic basalt erupted along the East Pacific Rise. This composition and the general tectonic setting led Elders and others (1972) to suggest that basalt xenoliths represent magma formed in the upper mantle beneath an active spreading center.

The granitic xenoliths contain textural evidence suggesting partial melting at depth, but isotopic data listed by Robinson, Elders and Muffler (1976) are not compatible with an origin of rhyolitic magma derived from the partial melting of granitic basement. $^{87}Sr/^{86}Sr$ ratios of 0.704 to 0.705 for the rhyolite are too low for the rhyolite to form from partial melting of granite (A granitic xenolith from Obsidian Butte has a $^{87}Sr/^{86}Sr$ ratio of 0.7119.). Thus Robinson, Elders and Muffler (1976) prefer a model of fractionation of primitive basaltic magmas from the upper mantle to derive both the basaltic and rhyolitic magmas. The isotope ratios for the rhyolite are higher than mantle-derived basalt and suggest that there has been some contamination by continental crust material. This conclusion is supported by the presence of granite xenoliths in the rhyolite.

Robinson, Elders, and Muffler (1976), and Elders and others (1972) interpreted the geologic and magnetic pattern in the Salton Sea geothermal field as being related to orthogonal faulting, and that the volcanoes lie on northeast-trending lineaments which are leaky transforms, presumably overlying a spreading center at depth.

TECTONIC SETTING OF THE VOLCANIC ROCKS

The following is a brief discussion of the tectonic setting of the volcanic rocks. A more complete discussion on the tectonic development of the Salton Trough is given by Terres and Crowell (Chap. 2, this volume).

Prior to 35 m.y. a period of magmatic quiesence existed in the Chocolate Mountains area, as noted by Lipman, Prostka and Christiansen (1972), and was part of the Great Basin null region (Snyder, Dickinson, and Silberman, 1976), and the diachronous magmatically quiet corridor of Cross and Pilger (1978). A lack of magnetic activity between 45 m.y. and 32 m.y. in Mexico has been reported by McDowell and Keizer (1977). Commencement of magmatic activity in the area east of the present-day San Andreas fault at about 35 m.y. (Fig. 19) was related to a southward shift in volcanism in Oligocene time (Lipman, Protska, and Christiansen, 1972). This volcanism produced volcanic Units A, B, and C_a and was part of a widespread igneous suite covering much of the western interior of North America. Lipman, Protska, and Christiansen (1972) showed the similarity of these rocks to circum-Pacific andesite suites, and suggested that the volcanic rocks were genetically related to a subduction system. Thus volcanic rocks of Units A, B and C_a are interpreted as part of a continental margin arc system. Atwater (1970) described possible plate movements related to a subduction system located off the North American coast during middle Cenozoic time.

Lipman, Protska, and Christiansen (1972) attempted a reconstruction of the geometry of the subduction zone for Middle Cenozoic time based on the K-h relationship recognized by Dickinson and Hatherton (1967) and refined by Dickinson (1975). Crowe, Crowell, and Krummenacher (1979) used these models to suggest

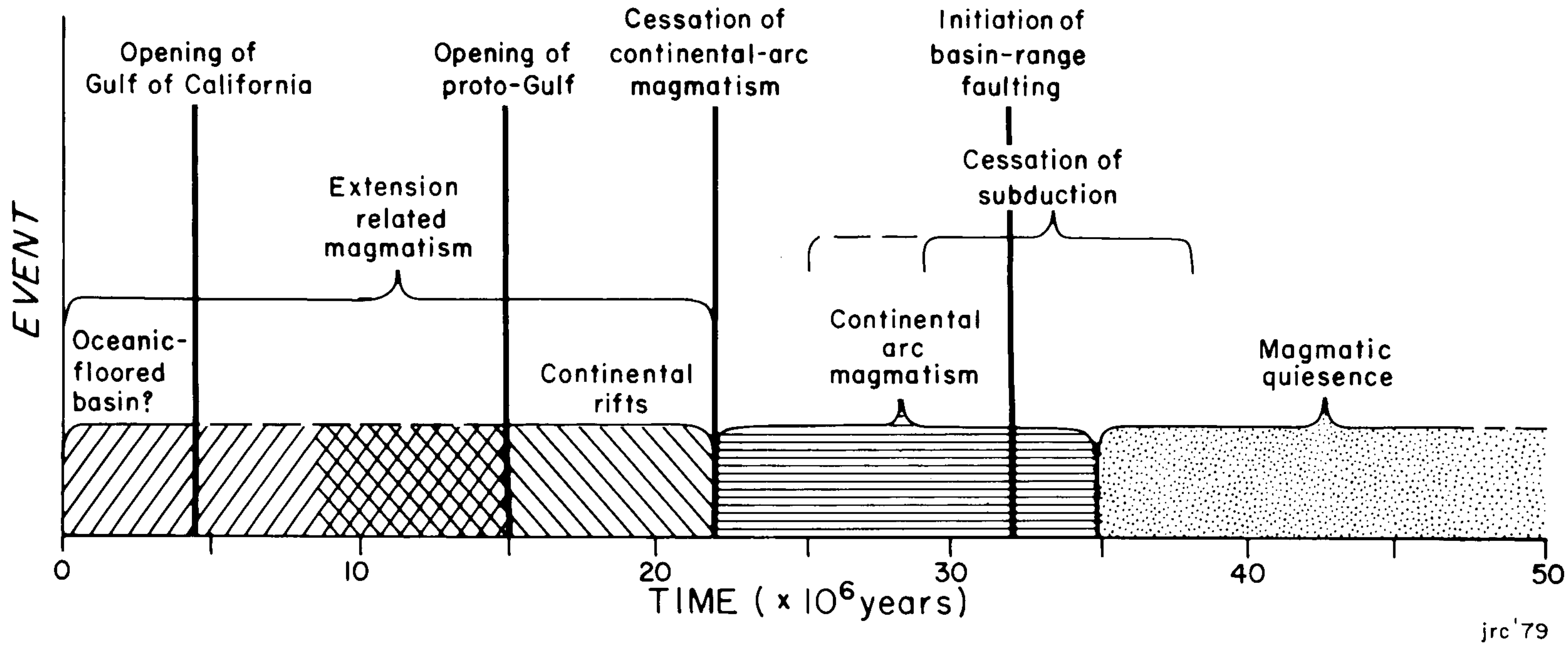

Fig. 19. Summary of tectonic events through time to which magmatic activity in the Salton Trough region might be related. Also shown is the distribution through time of the major episodes of continental arc magmatism and extension-related magmatism (see text for discussion).

that the depth to the top of the inferred subduction zone was approximately 190 km in the Chocolate Mountains.

The Pacific plate first encountered the North American plate sometime between 38 m.y. and 29 m.y. at a point somewhere west of the Salton Trough (Atwater and Molnar, 1973; Terres and Crowell, Chap. 2, this volume). One would expect a time lag between the cessation of subduction and the cessation of arc magmatism to account for the detached slab during descent. In the Chocolate Mountains the last episode of volcanism considered to be related to the subduction system is 22 m.y. (Crowe, Crowell and Krummenacher, 1979), and thus there appears to be a time lag of 7 m.y. to 16 m.y. after the Pacific plate encountered the North American plate.

Christiansen and Lipman (1972) documented a major change in the type of volcanism from calc-alkaline andesitic type to one dominated by basaltic magmatism. They interpreted this change in the tectonic regime as due to a change from a subduction-related system to one dominated by extension. Thus, the basaltic volcanism is considered to have accompanied regional strike-slip and normal faulting. Northwest-trending right-lateral faults such as the San Andreas, San Jacinto, and Elsinore fault zones now dominate the tectonic pattern in southernmost California (see Crowell and Ramirez, Chap. 3, this volume).

Younging toward the northwest in the age of initiation of basaltic volcanism was noted by Christiansen and Lipman (1972). The K-Ar age range from Unit C_b of Crowe, Crowell and Krummenacher (1979) of 13 m.y. - 22 m.y. (and more likely 13 m.y. - 19 m.y.) is considerably younger than the age of 26 m.y. - 23 m.y. previously cited by Christiansen and Lipman (1972). This suggests that the transition to basaltic volcanism in the Chocolate Mountains occurred much later than previously thought.

Crowe (1978) presented evidence to suggest that the inception of basin-range faulting commenced about 32 m.y. ago and was followed by the transition to basaltic volcanism which occurred much later at 22 m.y. - 13 m.y. The transition to basaltic volcanism also overlaps in time the probable age of inception of strike-slip faulting in the borderland of southern California (Howell, 1976; Graham and Dickinson, 1978). Thus, the volcanic rocks of Unit C_b appear to be related to extensional tectonics wherein strike-slip faults and continental rift zones were developing.

Hawkins (1970) found that basaltic volcanic rocks west of the San Andreas fault are spatially related to fault zones, and he inferred a genetic relationship between the faulting, volcanism and crustal dilation based on the spatial relationship and the chemistry of the basalts. Karig and Jensky (1972) and Moore (1973) suggest that a proto-Gulf of California came into existence during Middle Miocene time and probably existed until Pliocene time. From at least 7 m.y. to 4 m.y., little or no extension has been recorded in the Gulf (Karig and Jensky, 1972), and this corresponds to a notable lack of volcanic activity in the landward extension of the Gulf around the Salton Sea (Fig. 18).

The present Gulf of California commenced to open about 4.5 m.y. (Atwater and Molnar, 1973). At about the same time on land to the north, continental crust was being thinned beneath a widening and deepening rift system which was rapidly filling with sediments and being intruded by basaltic material. Volcanic rocks younger than 4.5 m.y. such as the Salton Buttes are chemically similar to rocks of the East Pacific Rise and suggest an origin related to crustal spreading, possibly along a leaky transform (Robinson, Elders, and Muffler, 1976).

In conclusion, the younger, fundamentally basaltic volcanic rocks in the southernmost California which are related to extensional tectonics might record a progression from continental rift zones to marginal basins floored by oceanic-type crust.

ACKNOWLEDGMENTS

I wish to thank J. C. Crowell for the invitation to participate in the preparation of this guidebook. J. C. Crowell and A. G. Sylvester kindly reviewed the manuscript. Several useful discussions were held with the writers of other articles in this guidebook, in particular R. Terres and B. Baca.

Chapter 10

SEDIMENTATION HISTORY OF THE SALTON TROUGH

by

John C. Crowell and Brian Baca

ABSTRACT

Sedimentary rocks exposed in the Salton Trough can be grouped into three sequences: (1) those strata older than either the proto-Gulf or the Gulf of California, such as the Eocene Maniobra, Oligo-Miocene Diligencia Formations, and probably the Miocene Anza Formation, (2) those laid down within the proto-Gulf, including the nonmarine Coachella Fanglomerate and Split Mountain Formations, and the marine Imperial (or Bouse) Formation, and (3) those strata deposited within the presently widening Gulf of California such as the nonmarine Palm Spring Formation with its coarse proximal facies (the Mecca and Canebrake Conglomerates) and distal fine-grained facies, the Borrego Formation. The youngest formations, of Pleistocene age, include the Ocotillo and Cabezon Fanglomerates and their fine-grained counterpart, the Brawley Formation.

Sediments as thick as 6 km apparently underlie deeper parts of the Salton Trough, and are largely Plio-Pleistocene in age. They have accumulated as the Gulf of California widened, and are undergoing metamorphism at depth in association with inferred spreading centers at the divergent plate boundary. Older strata, such as those deposited in the proto-Gulf, are envisioned as now being disrupted and occurring only around the trough margins. Older strata have also been offset by right slip along faults of the San Andreas fault system for many tens of kilometers, with the younger units displaced less than the older, in such a growing system. For example, Late Miocene fanglomerates have been offset more than 300 km from their source areas. The tectonic mobility of the region, involving both lateral and vertical movements, requires consideration in visualizing the distribution and origin of sedimentary facies. Conversely, it is the very study of facies and provenance that, in part, documents this mobility.

INTRODUCTION

Sedimentation today is actively taking place within the Salton Trough and has probably followed the same pattern back into Pliocene time as this landward apex of the Gulf of California opened and widened. Older sedimentary rocks document the history of the proto-Gulf back into Late Miocene time. Strata older than these, such as the Eocene Maniobra and Oligocene-Early Miocene Diligencia Formations of the Orocopia Mountains and the Anza Formation of the western margin of Imperial Valley were deposited under different tectonic settings before the proto-Gulf was born (Crowell and Susuki, 1959) and were not laid down within the Salton Trough itself. Here we describe briefly the nature and distribution of the sedimentary rocks of Miocene and younger age and draw inferences on what they inform us concerning the tectonic history.

Sediments accumulating within the Salton Trough today and in the immediate geologic past come from two distinctly different sources: from the Colorado River and from canyons debouching into the trough from surrounding highlands. Within the trough the Colorado River forms a low divide, about 11 m above sea level at its crest between the Imperial Valley and Salton Sea region on the northwest and the Mexicali Valley on the south. The Colorado River now enters the east side of the Salton Trough near Yuma at an elevation of about 43 m. From time to time floods carry sediments northwestward into the Salton Sea. This last happened during 1905 to 1907 when the river broke through its levees and formed the Salton Sea with a surface elevation presently about 71 m below sea level (Sykes, 1937). Prior to that event, the depression was dry, although earlier waters from the Colorado River fed prehistoric Lake Cahuilla. This lake occupied the Salton Trough at times between 300 and 1600 years ago as shown by radiocarbon dating of plant material (Hubbs and Bien, 1967). The region of the Salton Sea has therefore alternately filled and dried up as the Colorado River swung northward to flow into it, or southward into the Gulf of California. The sediments brought in by the river are dominantly very fine-grained and are characterized by high calcium carbonate content (Muffler and Doe, 1968; Van de Kamp, 1973). Reworked Cretaceous foraminifera from the Colorado Plateau are present locally (Merriam and Bandy, 1965).

Sediments derived from the walls of the Salton Trough form alluvial fans extending basinward with coarse boulder conglomerate at their heads and mud, silt, and fine sand at their distal ends. Where the stream gradients are relatively high, fanglomerate and braided-stream deposits are laid down and where the gradients on fans are low, deposition occurs in meandering channels. These facies, along with lacustrine sediments and patches of aeolian sand, have been mapped by Van de Kamp (1973). Complex interfingerings are recognizable where the sediments from the trough margins meet those from the dominating Colorado River delta. Presumably similar facies patterns exist at depth beneath the central part of the trough. Here about 6 km of strata are indicated by a few deep wells and geophysical interpretations (Keller, Chap. 6, this volume). The Standard Oil Company of California Wilson No. 1 well, drilled near Brawley, for example, penetrated about 4 km of Pleistocene and Recent fluviatile and lacustrine sediments (Muffler and Doe, 1968).

Lower Pleistocene and Neogene strata lie unconformably beneath younger beds along both the southwestern and northeastern margins of the Salton Trough (Dibblee, 1954). Facies similar to the younger sediments predominate except for marine units temporally near the Miocene-Pliocene boundary. The oldest sedimentary units so far recognized which were laid down within the Salton Trough are assigned to the Anza Formation and Coachella Fanglomerate of Middle and Late Miocene age, respectively. The main exposures of Neogene strata are in hills and mountains along the west side of Imperial Valley and the San Gorgonio Pass region, and in the Indio, Mecca and Durmid Hills. The stratigraphic relations among the various formations in Salton Trough are illustrated in Fig. 20.

CENOZOIC STRATIGRAPHY ALONG SOUTHWEST MARGIN OF SALTON TROUGH

Sedimentary rocks exposed in the Vallecito, Fish Creek, Coyote Mountains and Borrego Valley regions have a maximum thickness of about 5700 m (18,700 ft). The strata have been described primarily by Tarbet and Holman (1944), Tarbet (1951), Dibblee (1954), and Woodard (1974). The oldest units are assigned to the Anza Formation (Fig. 20) and lie nonconformably on pre-Cenozoic basement rocks (Woodard, 1974). The Anza Formation consists of about 540 m (1800 ft) of granitic boulder and cobble fanglomerate and coarse arkosic sandstone. Interbedded andesite and basalt flows, some dated in the region by K-Ar methods (Gastil, Krummenacher, and Minch, 1979), indicate that the formation is in part about 18 m.y. old (Early Middle Miocene) and older than the overlying Alverson Andesite having K-Ar ages of 16 ± 1.0 m.y. (Eberly and Stanley, 1978) and 13 m.y. (Sylvester and Smith, 1976). Flows of the Alverson Andesite nonconformably rest upon both granitic basement and upon beds of the Anza Formation about 8 km southeast of Split Mountain Gorge (Kerr and others, Chap. 11, this volume).

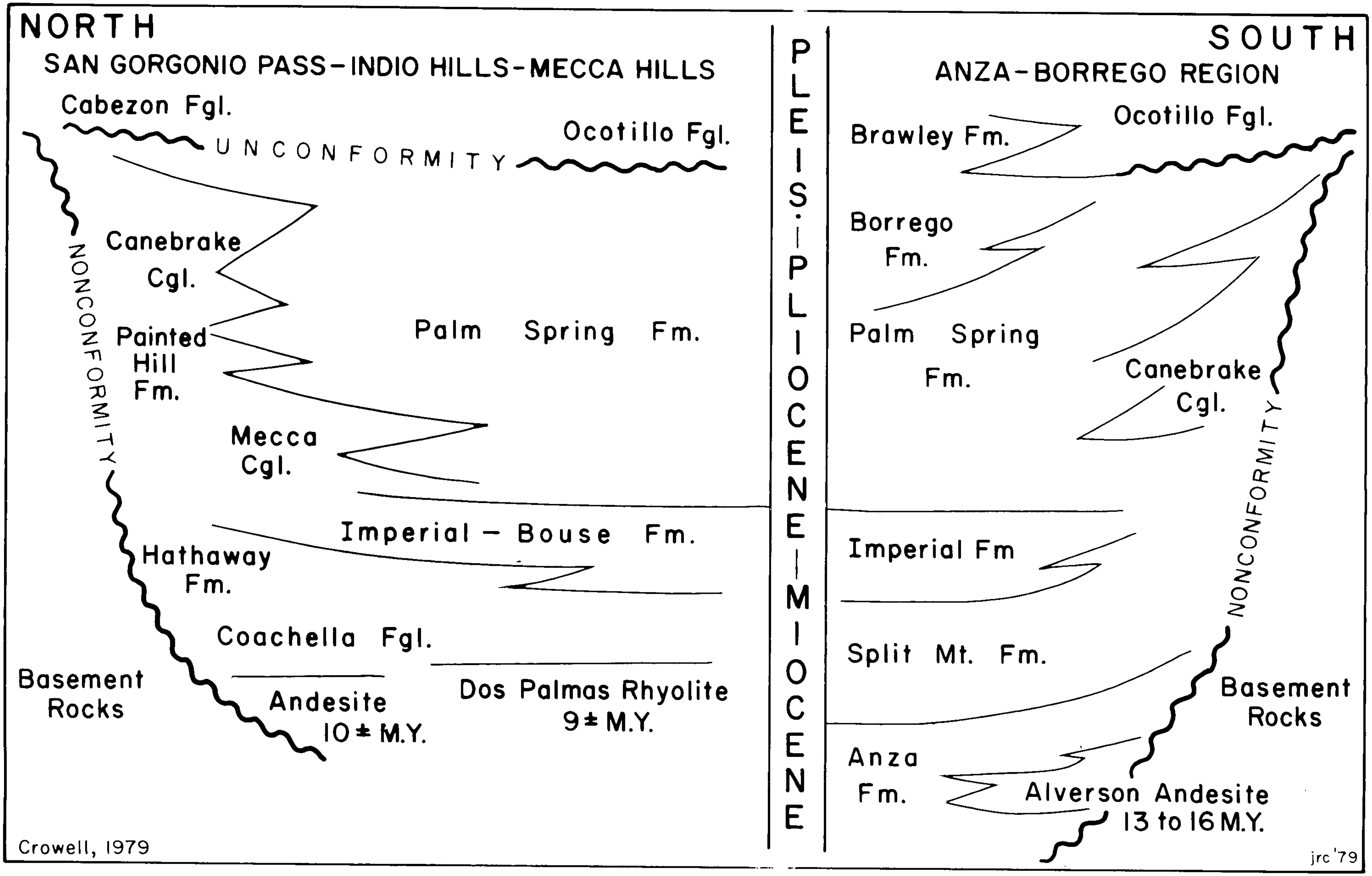

Fig. 20. Stratigraphic relations among Late Cenozoic formations in the Salton Trough region. Refer to text for explanation.

The Split Mountain Formation, with a maximum exposed thickness of about 270 m (850 ft) unconformably overlies the Alverson Andesite (Woodard, 1974). The formation includes very coarse boulder and cobble fanglomerate (some blocks are 4.5 m in length), marine sandstone and shale, and the Fish Creek Gypsum. Foraminifera from the marine shale led Tarbet and Holman (1944) to assign a Middle to Late Miocene age to this unit, but A.D. Warren (1972, in Gastil, Krummenacher, and Minch, 1979, p. 839) states that it is probably Pliocene.

The marine Imperial Formation, reaching a maximum of 1200 m (4000 ft) in thickness, unconformably overlies the Split Mountain Formation, the Alverson Andesite, and at places pre-Cenozoic basement rocks. It consists primarily of fossiliferous fine-grained sandstone, siltstone, mudstone, claystone and biostromal limestone. Marine bivalves, echinoids, corals, foraminifera, and bryozoans were first assigned to the Late Miocene (Woodring, 1932; Tarbet, 1951; Dibblee, 1954), but later paleontologists have favored a mostly Pliocene age (Durham and Allison, 1960; Smith, 1970; Ingle, 1973). In fact, Ingle (1973) correlated the foraminiferal assemblages with the open-ocean paleomagnatic-radiometric time scale and assigned a Late Miocene through Early Pliocene to both the Imperial and Bouse Formations. Thus, at least 8 m.y. ago an embayment of the sea occupied part of the region now included in the Salton Trough.

The Palm Spring Formation, from 2000 to 3000 m (7000 - 10,000 ft) thick, grades laterally into and overlies the Imperial Formation (Fig. 20). It consists predominantly of non-marine sandstone, siltstone, mudstone, conglomerate, and some beds of fresh-water limestone. A limited marine invertebrate fauna collected from the upper part of the formation indicates intermittent nearshore marine conditions existed in the Salton Trough as late as Middle Pleistocene time (Downs and Woodard, 1961). The Palm Spring Formation is mostly Pleistocene in age (Woodard, 1974), but parts may have been deposited during Late Pleistocene time. The Canebrake Conglomerate constitutes the western basin-margin facies of both the Imperial and Palm Spring Formations. The Truckhaven Rhyolite was named by Dibblee (1954, p. 24) for an extrusive wedge within the Canebrake Conglomerate in the northern San Felipe Hills, but it has been reinterpreted as a zone of silicified sediments (Weismeyer, 1968).

The upper part of the Palm Spring Formation grades eastward into lacustrine silt and clay of the Pleistocene Borrego Formation (Dibblee, 1954; Wagoner, 1977; Dronyk, 1977). The Borrego Formation, in turn, is overlain both gradationally and unformably by the Ocotillo Conglomerate and its eastern lacustrine facies, the Brawley Formation. The Ocotillo Conglomerate is up to 300 m

(1000 ft) thick and consists of gray granitic-pebble detritus and the Brawley Formation, 600 m (2000 ft) of silt, sand, and mud. Both the Brawley and Borrego Formations contain a lacustrine fauna of mollusks, ostracods and foraminifera (Dibblee, 1954), and are interpreted as deposited in a nearshore lacustrine environment (Wagoner, 1977). Overlying these strata are Uppermost Pleistocene and Recent units of fanglomerate, terrace deposits, and alluvium. Deposits laid down on the floor of Lake Cahuilla which only dried up about 300 years ago, are widespread. Sand bars and spits are well developed near the old shorelines, and the floor of the ancient lake is mantled with fine sand and silt containing tiny mollusks which are picked up by the wind at places and concentrated in wind rows.

CENOZOIC STRATIGRAPHY ALONG NORTHEAST MARGIN OF SALTON TROUGH

Miocene and younger sedimentary rocks are well exposed in four areas bordering the Salton Trough on the north and northeast: the San Gorgonio Pass region, Indio Hills, Mecca Hills, and Durmid Hills. Older sedimentary units crop out in the eastern Orocopia Mountains but were deposited in different tectonic settings, before the origin of the present Salton Trough, and the proto-Gulf of California. These older units include the Maniobra Formation (Eocene) and the Diligencia Formation (Oligocene-Early Miocene) (Crowell, 1975b). In addition, local patches of Miocene sedimentary strata are intercalated with dated volcanic rocks in the Chocolate Mountains (Crowe, 1978; Crowe, Crowell and Krummenacher, 1979).

The Coachella Fanglomerate, exposed in the eastern part of the San Gorgonio Pass region, is the oldest sedimentary unit so far recognized whose facies show that it was deposited within the Salton Trough along its northeastern margin. It consists of up to 1500 m (4500 ft) of fluviatile coarse conglomerate and debris-flow sedimentary breccia, and minor sandstone (Allen, 1957; Proctor, 1968; Peterson, 1975) lying unconformably on basement complex. Near the base of the formation is an interbedded flow of andesite breccia, dated at 10 ± 1.2 m.y. by K-Ar methods (Peterson, 1975) which places the eruption of the andesite unit in Late Miocene time. Paleocurrent indicators, thickness changes, and diminution downflow in stone size show that the fanglomerate was derived from the north, and from a source now across the northern branch of the San Andreas fault (Mission Creek fault). A possible source area containing rocks matching distinctive clasts of porphyritic quartz monzonite and magnetite has been recognized near the Cargo Muchacho Mountains, a suggested correlation that requires 215 km of right slip (Peterson, 1975). The Hathaway Formation consisting largely of conglomerate and sandstone in the San Gorgonio Pass region probably overlies the Coachella Fanglomerate and underlies the Imperial Formation (Allen, 1957; Proctor, 1968).

The marine Imperial Formation, consisting of yellow-brown and greenish mudstone, siltstone, sandstone, and a few interbeds of conglomerate, unconformably overlies the Coachella Fanglomerate in the eastern San Gorgonio Pass region (Allen, 1957; Proctor, 1968). From this region it apparently thickens southeastward to a maximum so far reported of 500 m (1660 ft) in the Texas Edom well drilled in the western Indio Hills a kilometer south of the south branch of the San Andreas fault (Banning fault). The easternmost exposure in this general region lies near the juncture between the two branches of the San Andreas fault, north of the town of Indio (Proctor, 1968). It has not been found north of the northern branch. The age of the Imperial Formation, judging from faunas, is usually given today as Early Pliocene, but some controversy still remains so that lower parts may be Late Miocene (Woodring, 1932; Durham and Allison, 1960).

Metzger (1968) named the Bouse Formation for marine beds of similar aspect to the Imperial Formation found along the Colorado River in the Parker-Blythe-Cibola region. Brackish and marine faunas, but especially a K-Ar minimum date of 3.02 ± 1.15 m.y. on an interbedded tuff (Damon, 1967, in Metzger, 1968, p. D133), indicate that the formation is primarily Early Pliocene in age. The Bouse Formation was apparently deposited in a north-trending marine embayment extending into southern Nevada and northwestern Arizona with shorelines that have now largely been eroded away or buried beneath younger basin fill (Metzger, 1968; Blair, 1978). The formation probably correlates with the older named Imperial Formation. Pliocene and younger right slip on the San Andreas fault may have offset the Bouse from the Imperial in the Coachella Valley region. The record is too piecemeal, however, to reconstruct thickness- and facies-change lines in order to establish slip.

Within the Mecca Hills, the Mecca Formation lies nonconformably upon basement terrane, and thickens markedly toward the southwest (Sylvester and Smith, 1976). In this direction as well as upward in the stratigraphic section it intertongues with the Palm Spring Formation. The Mecca Formation consists primarily of brown conglomerate and sandstone characterized by angular, locally derived gneiss and schist detritus. The largely overlying Palm Spring Formation, however, consists of tan sandstone and drab siltstone with conglomerate beds in which granitic detritus prevails. These differences reflect source areas: as the drainage areas worked headward more and more granite terrane was tapped, especially in the Little San Bernardino-Cottonwood-Eagle Mountain chain, as the local prevailing gneiss was overlapped by large, southwest-directed coalescing alluvial fans. The Mecca Formation reaches a maximum thickness of about 180 m (600 ft) whereas the Palm Spring reaches 1500 m (4800 ft) (Dibblee, 1954). Conglomerate tongues in the middle and upper Palm Spring Formation dominated by granitic cobbles, are called Canebrake Conglomerate (Dibblee, 1954). The exposures of these nonmarine, non-fossiliferous formations lie largely within and northeast of the San Andreas fault zone. Their thickness changes and facies reflect sedimentation at the edge of a deepening trough with a platform-like margin upon which the beds overlap. The thick units of the Palm Spring Formation, however, were largely dumped into the growing trough southwest of the San Andreas fault (Sylvester and Smith, 1976). The Mecca and Palm Spring Formations are also exposed in the Indio Hills (Popenoe, 1958), and the 760 m (2500 ft) of strata within the Durmid Hills northeast of the San Andreas fault, assigned by Babcock (1974) to the Shavers Well Formation of Hays (1957), probably constitute a distal facies of the Palm Spring. The Painted Hill Formation of the eastern San Gorgonio Pass region probably correlates with the Palm Spring as well (Allen, 1957; Proctor, 1968).

The age of the Mecca-Palm Spring sequence is probably Late Pliocene and Pleistocene inasmuch as a few vertebrate remains of this age have been recovered from the upper part of the Palm Spring Formation in the central Mecca Hills (Hays, 1957). The units are younger than the Dos Palmas Rhyolite, with a K-Ar date of about 9 m.y. (Sylvester and Smith, 1976) which lies as flows nonconformably upon basement rocks and beneath coarse conglomerate correlated with the Mecca-Palm Spring in the eastern Mecca Hills. Unfortunately from the viewpoint of dating, the Imperial Formation is not exposed in the Mecca Hills, but strata assigned to the Palm Spring overlie the Imperial within the Indio Hills. Interpretations of the depositional environment and inferred age make it unlikely that the Mecca Formation correlates with either the Anza or Split Mountain Formations of the western Imperial Valley area; the Mecca Formation is considered here as considerably younger.

Units consisting of Pleistocene fanglomerate grading laterally into lacustrine silt are widespread and have been assigned to several formations. On the northwest, deformed fanglomerate beds have largely been assigned to the Cabezon Fanglomerate (Allen, 1957) whereas in the Indio and Mecca Hills, they are termed the Ocotillo Conglomerate (Dibblee, 1954; Proctor, 1968). In the Durmid Hills, lacustrine silt and sand are placed in the Borrego

Formation. Alluvium, wind-blown sand, and deposits from dessicated Lake Cahuilla make up the youngest mappable units.

SUMMARY

The sedimentary record within the Salton Trough documents three depositional stages. First, beds of the Anza Formation were deposited in a basin-range-type setting in which coarse debris accumulated in a local basin during Middle Miocene time. Second, patches of both marine and nonmarine beds around the margins of the present Salton Trough were laid down in a proto-Gulf in the Late Miocene and Early Pliocene. The site was an embayment east of the Peninsular Ranges that extended northward into the developing Basin and Range Province. From the age of the sedimentary rocks and associated volcanic rocks we infer that this proto-Gulf was in existence by 8 m.y. ago (Latest Miocene) and originated shortly before. Third, strata were later laid down within the Salton Trough, envisioned as the northwestern narrow end of the Gulf of California more or less as we know it today.

Divergence at this plate boundary began to operate about 4 m.y. ago and continues today. In doing so it has widened the older strata of the proto-Gulf. The transform faults represented by the San Andreas, San Jacinto, and Elsinore are pictured as developing right slip vigorously during these movements, but with marked dip-slip components along the braided fault zones. Although most of the sediments come from the mountains bounding Salton Trough and the Colorado River, blocks between and within the fault zones were carried upward to make local sediment sources; other blocks were depressed to provide local depositional basins. The documentation of this tectonic style comes largely from interpretation of the sediments, but studies are still far from being complete enough to fill in the details.

There are significant stratigraphic consequences of this tectonic and sedimentary history. Sedimentary units deposited in local basins and in the proto-Gulf are now grossly disrupted by later tectonic movements, including right slip of many tens of kilometers on strands of the San Andreas system. In addition, strata laid down when the opening Gulf was small cannot now extend all the way across the Salton Trough after it has widened to its present size. Moreover, spreading centers with associated mantle diapirs are pictured at depth, especially beneath Imperial Valley, where they invade sediments accumulating there now and in the immediate geological past. In this realm of the divergent plate boundary, although it is annealed at the surface by the inflood of sediments, only younger beds occur at depth, and these are undergoing metamorphism. This reconstruction implies that there is no true floor of older basement to the Salton Trough. Instead, more and more volcanic rocks, both flows and irregular intrusions, can be expected in going deeper which in turn pass into those of the spreading center itself, and eventually into mafic and ultramafic rocks from the upper mantle (Crowell, 1974b). Deep wells drilled in this inferred spreading-center region cannot reach "basement" but will presumably pass downward through this complex intermixture of sediments and volcanic rocks into a hot geothermal environment where, with increasing depth, the mafic rocks prevail. Only isolated bodies or floaters of the older wall rocks can be expected, now left behind as separated slices as the plate-margins diverged.

This reconstruction contains implications concerning correlation problems. Late Miocene strata laid down along the southwestern flank of the Chocolate Mountains to constitute the Mint Canyon Formation are now found about 300 km to the northwest in the north-central Transverse Ranges. Strata of about the same age, such as the Split Mountain and Coachella Formations, lie south of the main break of the San Andreas, and have been offset about the same amount. Their counterparts northeast of the San Andreas, if preserved, should be found in northern Sonora. Moreover, it seems reasonable that these two formations were more closely grouped, both before this disruption and before divergent movement on Salton Trough spreading centers. The younger Imperial (Bouse) Formation has participated in this right-slip disruption as well. All of these concepts need to be kept in mind and tested as facies studies continue in the Salton Trough region. This complex history may unfold as information comes in from paleocurrent, facies, provenance and thickness-change studies.

Chapter 11

NEOGENE STRATIGRAPHIC SECTION AT SPLIT MOUNTAIN, EASTERN SAN DIEGO COUNTY, CALIFORNIA

by

Dennis R. Kerr, Steve Pappajohn and Gary L. Peterson
Department of Geological Sciences
San Diego State University
San Diego, CA 92182

A spectacular section of Neogene rocks exposed at Split Mountain in eastern San Diego County consists of six distinctive rock units. The lower three are nonmarine and include (in ascending order) braided stream deposits, alluvial fan deposits, and a landslide deposit. All are apparently of Miocene age, and have been assigned by previous workers to the Anza and Split Mountain Formations. The upper rock units (Pliocene) are paralic or marine and include the Fish Creek Gypsum, turbidite deposits and a second landslide-debris flow deposit, included tentatively within the Imperial Formation. Together, these rock units record the initial tectonic subsidence within the Salton Trough region probably both before and during the origin of the proto-Gulf of California. They include the first indication of marine sedimentation associated with the Gulf.

INTRODUCTION

A Neogene stratigraphic section representing the lower part of the Salton Trough fill is spectacularly exposed at Split Mountain where downcutting by Fish Creek has created a gorge with near-vertical walls. The 400-feet-high cliffs offer a view through the south limb of a faulted NW-plunging anticline (Fig. 21). The section is readily accessible by an unimproved road through Fish Creek Wash.

Stratigraphic nomenclature for the western margin of the Salton Trough is complicated and controversial. Early investigators referred to the basal 2700 feet of fanglomerate, breccia

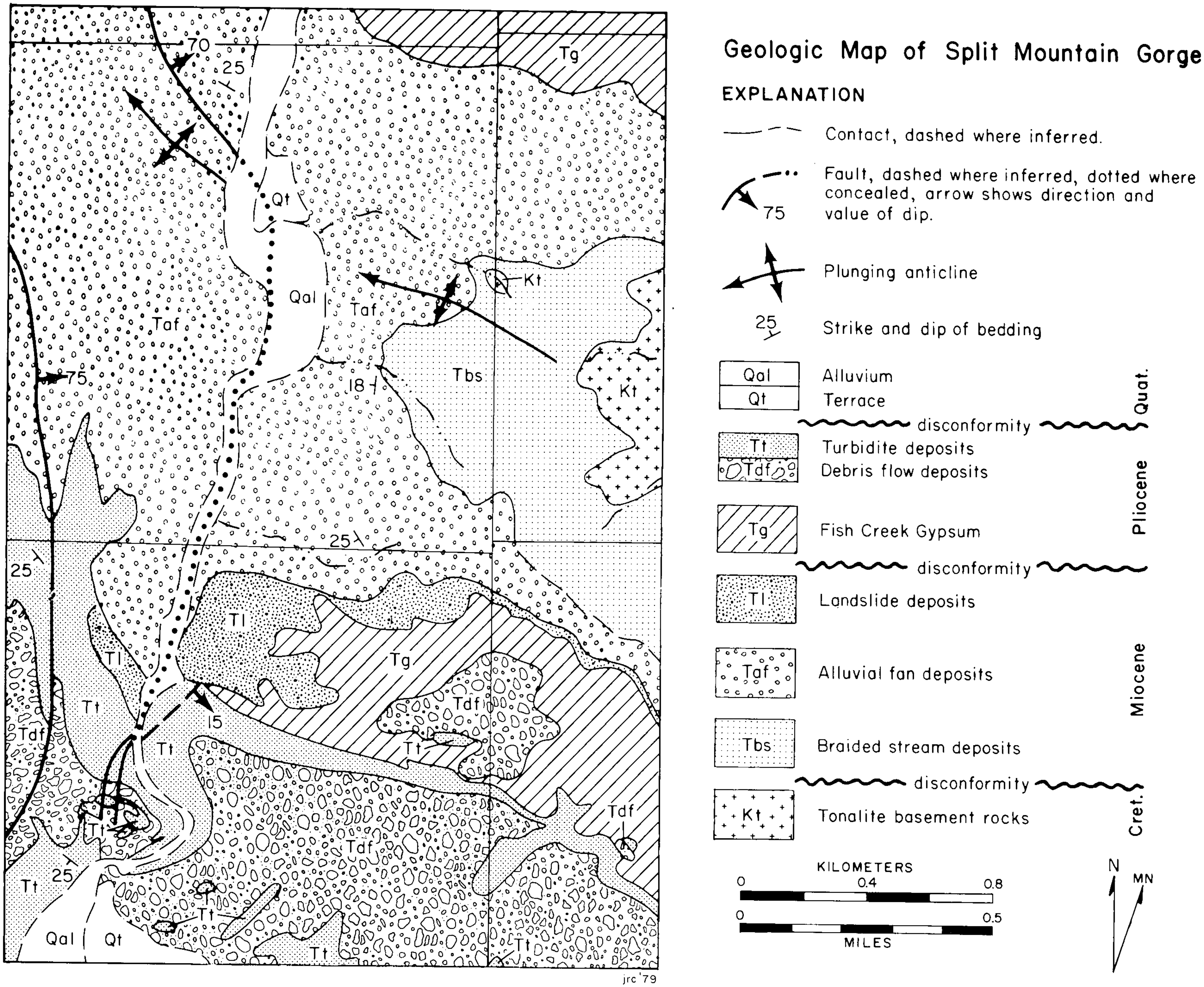

Fig. 21. Geologic map of the Split Mountain Gorge area, eastern San Diego County, California.

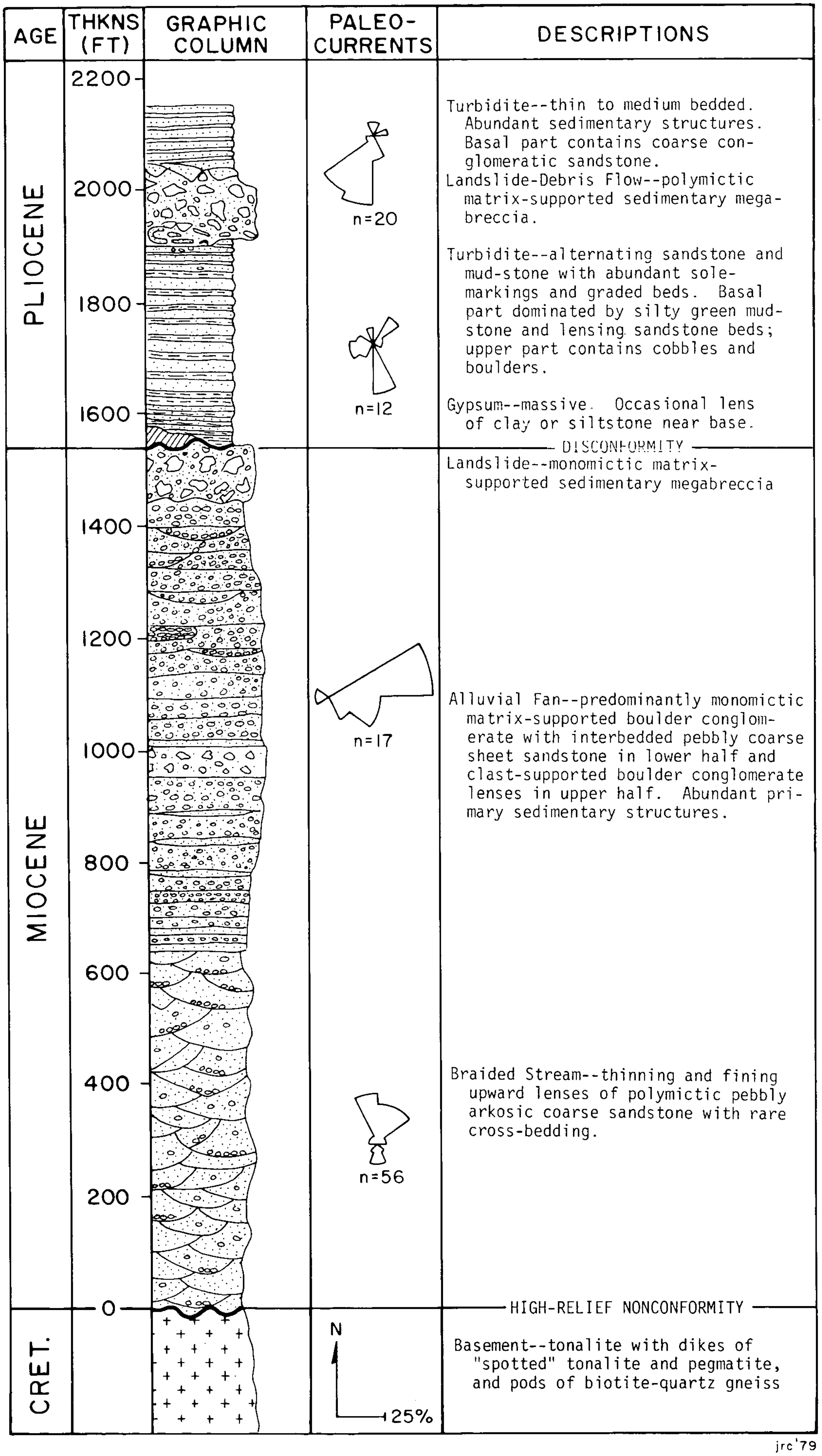

Fig. 22. Columnar section for Split Mountain Gorge.

and marine sandstone exposed at Split Mountain as the Split Mountain Formation (Tarbet and Holman, 1944; Tarbet, 1951; Dibblee, 1954). This formation rests unconformably on Cretaceous basement rocks and is overlain by marine mudstone generally regarded as the Imperial Formation.

For a variety of reasons, we do not agree with this subdivision, nor do we agree with a revision proposed by Woodard (1974). However, guidebooks are neither suitable for proposing new nomenclature nor revising old. We recognize two principal stratigraphic units in the Split Mountain section: (1) a lower nonmarine unit consisting of braided stream deposits, alluvial fan deposits, and a large landslide deposit, and (2) an upper paralic and marine unit consisting of the Fish Creek Gypsum, turbidite deposits, and a second landslide-debris-flow deposit. We tentatively suggest that the largely marine unit consisting of the section should be incorporated as part of the Imperial Formation, although it represents an unusual local facies. The lower nonmarine part of the section is tentatively regarded as Split Mountain Formation in the sense that Dibblee (1954) used this name in all sections except the type section at Split Mountain. Nomenclatural problems and possible solutions will be discussed in a future paper. The purpose of this paper is to describe briefly and to interpret the rock units exposed in Split Mountain Gorge.

This article represents a preliminary report on MS thesis work now in progress at San Diego State University. Dennis Kerr assumes responsibility for the lower nonmarine rocks, and Steve Pappajohn is primarily responsible for the upper marine rocks. Gary Peterson serves as supervisor and coordinator of these efforts. We acknowledge T. H. Nilsen and R. L. Threet for their invaluable discussions and express appreciation for the cooperation and interest of employees at the Anza-Borrego Desert State Park, especially M. Getty and F. Jee. Amoco Production Company and Standard Oil Company of California provided partial support for the investigation.

BASEMENT ROCKS

The basement complex is not exposed in the gorge proper, but crops out within the core of Fish Creek anticline to the E (see Fig. 21) and along the upthrown side of a fault to the W. Both exposures are within easy walking distance from the gorge. Outcrops of the basement rocks are generally weathered and extremely jointed and in most areas form rubble-strewn slopes, so that it is difficult to differentiate between the basement rocks and overlying conglomerate and breccia where exposures are poor.

The basement complex is dominated by light gray, medium-grained tonalite composed of 30% quartz, 50% plagioclase, 10% K-feldspar and 10% biotite. Dikes of "spotted tonalite," white aplite, and pegmatite cut across the tonalite. As the name suggests, the spotted tonalite is peculiar in that it consists of 1-inch "spots" of a medium-grained plagioclase-quartz-sphene assemblage, which is randomly distributed in a medium-grained matrix of abundant biotite, plagioclase, quartz, and rare sphene (Stensrud and Gastil, 1978). Also present are small pods of dark gray biotite gneiss. The local plutonic basement is considered part of the Southern California batholith of Cretaceous age (Dibblee, 1954).

BRAIDED STREAM DEPOSITS

The lowest Neogene rock unit is not exposed in the gorge proper, but crops out in the anticlinal core less than 0.5 miles E of the prominent bend at the lower (north) end of the gorge (Fig. 21). Here the deposits rest on a high-relief erosion surface cut into the basement rocks. The exposed thickness ranges up to 650 feet. About 1 miles E of Split Mountain Gorge these braided-stream deposits pinch out between the overlying alluvial fan facies and the basement rocks. The deposits probably do not extend W of the gorge into the subsurface, for here the alluvial fan deposits likewise rest directly on basement rocks. Thus the outcropping geometry of the braided-stream deposits indicate a generally N-S elongate lens.

The most conspicuous feature of the braided stream deposits is the stacked lenticular nature of these pinkish coarse arkosic pebbly sandstone beds. Each lens shows a general fining- and thinning-upward sequence. The sequence typically begins with about a 9-foot-thick package of massive clast-supported pebble conglomerate or locally large-scale trough-cross-bedded coarse sandstone representing rapid channel fill and channel dunes respectively. This in turn grades upward to another generally 9-foot thick package of thinning-upward massive, or small-scale, low-angle trough- or tabular-grouped cross-bedded coarse sandstone, the latter representing migrating ripples and accretionary bar development. The sedimentary structures and thinning-upward bedding in the upper package were formed either during waning floods or as up-channel avulsion occurred. This assemblage of of physical features is the result of rapid vertical decrease in flow competence, which is typical of braided stream conditions (Smith, 1970).

Gravel-clast populations and paleocurrent directions suggest that the braided-stream deposits had both local and distant sources and were probably deposited in a through-flowing drainage system. Gravel clasts from the underlying basement rocks are present throughout and constitute about 95% of the populations. The remaining 5% of the clasts are apparently extra-regional. Near the base are volcanic clasts identical to those found in the Table Mountain Gravels at Jacumba (Minch and Abbot, 1973), and "Poway clasts" identical to those of the Poway conglomerates and Ballena gravels of the San Diego area (Minch, 1970). The presence of volcanic clasts in the upper one-third of this facies was first noted by Woodard (1974) and is confirmed by this study. These clasts are derived from the Alverson Andesite, a Miocene volcanic unit which generally overlies the Split Mountain Formation at a number of localities to the S. The presence of Alverson clasts in the Split Mountain Formation at this and several other locations indicates that the Split Mountain and Alverson Formations are at least in part contemporaneous.

Unidirectional crossbedding and gravel fabric both strongly trend northward with bidirectional channel orientations supporting this same trend (Fig. 22). Thus the headwaters of the braided-stream drainage system were probably 25 or more miles to the S in the Peninsular Ranges with most of the sediment being derived from local basement sources. During the later history of the facies, Miocene Alverson volcanics from the southern Fish Creek Mountains about 5 miles to the southeast became an important additional source.

The physical features of this facies suggest that it was deposited under braided stream conditions (Miall, 1977), and the presence of Alverson volcanic clasts indicates that these deposits are Middle Miocene and/or younger in age, but perhaps the oldest are Early Miocene. Furthermore, the paleocurrent trends and gravel populations indicate that the preserved deposits were part of a more extensive fluvial system than what might be suspected from its isolated exposure at Split Mountain. Thus, the lowest facies represents an alluviated valley occupied by braided channels. The river had a large drainage basin and probably flowed northward beyond the Split Mountain area.

ALLUVIAL FAN DEPOSITS

Over half of the section exposed in Split Mountain Gorge is dominated by spectacular bedded conglomerate of the alluvial-fan facies, and the exposures offer a cross-sectional view through various subfacies of an ancient alluvial fan. Three types of sedimentologic processes are inferred to have deposited this facies: debris-flow, sheetflood, and fluvial-channel fill. Debris-flow deposits dominate the section and are characterized by matrix-supported conglomerates. The matrix is composed of varying ratios of sand-and finer-sized particles, whereas the suspended gravel clasts vary considerably in size from granules to large boulders. Bedding ranges from inches to 30 feet or more. Maximum clast size is generally proportional to bedding thickness. The debris-flow deposits also contain a number of fabric features such as normal, reverse, and symmetrical grading, and both horizontal and vertical long-axis clast orientations. These features are all typical of sedimentation by debris-flow processes (Johnson, 1970; Bull, 1972; Middleton and Hampton, 1973).

Sheetflood deposits are recognized by a vertical progression of grain size and sedimentary structures which indicate a rapid decrease in flow competence. The following vertical sequence is typically incomplete and only locally can it be observed in the entirety: basal granule to pebble gravel, gradationally overlain by small-scale, very low-angle trough cross-bedded coarse sandstone, grading upward to a massive coarse sandstone with an upward increase in biotite, to a 1/2-inch-thick biotite-rich coarse sandstone laminae. As the name implies, these deposits are sheets with bedding thicknesses generally averaging about 1 foot. Bull (1977) described sheet floods as surges of sediment-laden water. When not restricted by a channel, the sheet flood spreads out forming shallow channels which rapidly fill and laterally shift a short distance, thus creating a sheet of sand and gravel.

Fluvial channel-fill deposits represent the back-filling of entrenched channels and are characterized by poorly stratified clast-supported conglomerates that are lenticular in cross-section. Together these deposits, and the processes that created them, are typical of alluvial fans (Bull, 1972; 1977).

The relative abundance of the various types of deposits, the bedding character, and the general grain size variations give an approximate indication of distance from the fan head. The most distal part or subfacies, common to the lower part of the section, is interpreted from the abundance of sheetflood deposits and debris-flow deposits with the largest clasts being 3 feet in diameter. Bedding is well developed with a maximum thickness of 4 feet and width/thickness ratio equal to 300.

Farther up-section, 3-foot-thick sheetflood deposits are regularly interbedded with thick (up to 40 feet) debris-flow deposits which give an organized appearance to stratification. The largest clasts are about 6 feet in diameter. This subfacies probably represents a midfan region where debris flows are deposited as thick lobes and, as flood discharge wanes, a sheetflood spreads out over the lobe surface.

Toward the top of the section, channel fill deposits are more abundant until they almost equal the number of debris-flow beds. Sheetflood deposits are not present. The most striking feature of this upper subfacies is its unorganized appearance which is the result of poor stratification and erosional contacts. Here boulders are as large as 10 feet in diameter and the width/thickness ratio is about 40. This upper subfacies probably does not represent the fan head but rather an area high on the fan where both deposition and erosion took place.

The vertical change in subfacies indicates a prograding history for this fan. Outside of the gorge, the distribution of these subfacies suggests that the fan head was W of the gorge; this is also supported by the few paleocurrent indicators noted (Fig. 22). The apparent wedge-shaped geometry of this facies also suggests that the fan head is to the W. The maximum preserved thickness is about 1500 feet just NW of the gorge. Farther to the NW the fan deposits appear to thin and are eventually covered by Quaternary deposits. Approximately 2 miles to the SE, the fan deposits pinch out between the overlying facies and basement rocks and are considerably thinner along the N flank of the anticline than along the S flank (Fig. 21).

The second rock unit clearly indicates a prograding, debris-flow dominated alluvial fan. Coarse detritus was eroded from the Vallecito Mountains and carried east by debris-flow and fluvial transport. The sediment accumulated as a fan along the tectonically active margin of an alluviated valley represented by the underlying facies. Conformable and locally gradational contact relationships with the braided-stream deposits and the oblique nature of paleocurrent trends of the two facies (Fig. 22) support this interpretation. The probable margin of the basin is still marked by an active NW-trending fault 3 miles to the W (see Dibblee, 1954, pl. 2).

LANDSLIDE DEPOSIT

Overlying the alluvial fan deposits is a striking landslide deposit. This unusual cliff-forming lithofacies apparently has a tabular geometry from its fairly uniform thickness of about 150 feet over about 3.5 miles of outcrop (Figs. 21 and 22). It abruptly pinches out in the W wall of the gorge, and extends to the SE where it abuts against the Fish Creek Mountains. The lower contact is undulatory and is concordant with the underlying alluvial-fan facies which commonly is disrupted near the contact. The upper contact forms a hummocky surface. The deposit is a massive sedimentary megabreccia with large (up to 15 feet in diameter) tonalite boulders suspended in a greenish gray sandy mud matrix. Many clasts can be visually put back together with adjacent clasts, like pieces of a giant jigsaw puzzle.

An ususual origin is required to explain this peculiar rock unit with its tabular shape and contact features. Robinson and Threet (1974) suggested that the megabreccia was catastrophically deposited in mass. They further argued that it represents a rock-slide that traveled on a cushion of air, similar to a mechanism proposed by Shreve (1966; 1968a; 1968b). Slides of this type are initiated by a large rockfall that entraps air as it falls. The debris then is capable of traveling with little internal deformation at high speed for several miles. When the entrapped lubricating layer escapes from beneath, the mass comes to a sudden and dramatic halt which causes intense internal deformation (i.e., brecciation) and could very well disrupt the surface upon which it comes to rest. At present, it is difficult to determine the source of this slide, but Robinson and Threet (1974) suggested that it was derived from the Fish Creek Mountains to the E.

FISH CREEK GYPSUM

Although not present at Fish Creek Wash level, the Fish Creek Gypsum (Ver Plank, 1952; Dibblee, 1954) forms white, smooth, rounded slopes high atop the eastern wall of Split Mountain Gorge. The lithofacies generally consists of massive 1- to 3-foot-thick beds of white or light gray to blue gypsum. Clear sheets of selenite are present locally throughout, and anhydrite occurs near the base. Greenish gray mudstone lenses are also present locally and are more common toward the top of the deposit. The high quality and quantity of the gypsum is of economic significance and is presently being mined by the U.S. Gypsum Company.

The lateral relationships and geometry of the gypsum body suggest a complex environment of deposition. A narrow digitation of gypsum and green mudstone of the overlying marine facies is exposed about 150 feet E of Fish Creek Wash above the disconformable contact with the underlying landslide facies. The same relationship occurs on the north flank of the Fish Creek anticline. However, here the green mudstone (which is included in the Imperial Formation by Dibblee, 1954, pl. 2) is intimately associated with paralic deposits. At the U.S. Gypsum quarry, approximately 1.5 miles NE of Split Mountain Gorge, the gypsum is apparently the lateral equivalent of both alluvial fan and marine deposits. Approximately 3 miles to the E, thick erosional remnants of gypsum rest nonconformably on basement rocks. According to U.S. Gypsum tests, the thickest deposits lie under the synclinal valley NE of Split Mountain Gorge. Maximum exposed thickness is about 120 feet.

TURBIDITE DEPOSITS

The exposures in the gorge reveal a vertical gradation from green mudstone constituting the lateral equivalents of the Fish Creek Gypsum, to rhythmically bedded turbidite sandstone of Pliocene age (Stump, 1972). From a maximum thickness of about 300 feet exposed at the S end of the gorge, this facies abruptly interfingers with the same green mudstones less than 1 mile to the E. About 1.5 miles to the NW, the turbidites grade laterally into a poorly defined paralic zone and distal alluvial fan deposits. The non-marine alluvial-fan deposits are not the same as the previously described fan facies, but rather rest disconformably on the earlier alluvial-fan deposits. An overlying landslide-debris-flow facies, which will be discussed below, interrupts this mode of deposition. Overlying the debris-flow deposit, more turbidites are preserved in the exposures S of Split Mountain Gorge where green mudstone layers are progressively more dominant. The marine sandstone and mudstone above the landslide-debris flow facies have been included in the Imperial Formation by all previous workers (Tarbet and Holman, 1944; Tarbet, 1951; Dibblee, 1954; Woodard, 1974).

Rock types of this facies are characteristic of turbidites, a term which is here used in the same sense as Nilsen (1977). The sandstones are arkosic in composition and commonly exhibit normal grading from coarse sand at the base of some beds to fine sand at the top. Sandstone bedding thicknesses average 1 to 4 feet and beds are laterally continuous. Thinly bedded (3 to 6 inches) siltstone is less common and consists of lenticular packages between sandstone with green mudstone being more common higher in the section. Sedimentary structures include sole marks such as groove casts, some nearly 30 feet in length, and well-developed flute casts; both are more abundant higher in the section due to an increase in mud which is more easily eroded by sedimen-transporting mechanisms. Sand injections, flames, and rip-up clasts are common features of the sandstone beds in the gorge because of the lower mudstone content. Biogenic structures are common throughout the turbidite facies. Sandstones are present as thinning- and fining-upward sequences, about 10 to 20 feet in thickness, that contain Bouma (1962) A, E divisions in the lower part of the section and complete A-E divisions in the upper part of the section.

The sedimentary features of these sandstone beds indicate deposition by turbidity currents, although other sediment gravity-flow mechanisms may have been involved (Middleton and Hampton, 1973). In addition, the thinning- and fining-upward character suggests that these strata were deposited in channels of varying size, and the related siltstone layers probably represent deposition in interchannel areas (Mutti and Ricci Lucchi, 1978).

Paleocurrent trends indicate that sediment was transported to the SE in the lower part of the section and to the SW above the landslide-debris flow facies (Fig. 21). A southward paleoslope is also indicated by the stratigraphic relationship between the turbidites and laterally equivalent alluvial fan deposits to the northwest.

LANDSLIDE-DEBRIS-FLOW DEPOSITS

Within the turbidites is a second megabreccia deposit, exposed at the head of Split Mountain Gorge. It is a massive, poorly sorted, megabreccia with clasts of tonalite, pegmatite, schist, gneiss and marble of cobble to large boulder sizes, some in excess of 30 feet in diameter, suspended in a green-gray to reddish brown matrix. Also present in the vicinity of the gorge are rip-up clasts of the turbidite facies incorporated as part of the megabreccia. Just E of the gorge, rip-up clasts and flaps (megaflames) of turbidites attain dimensions that are mappable at 1:24,000 scale. The megabreccia deposit is apparently tabular in shape with a maximum thickness of approximately 120 feet and extends for about 2 miles both E and W of Split Mountain Gorge.

Like the lower landslide facies (Fig. 21), this facies requires an unusual origin. However, because of its association with adjacent facies and the lateral changes in composition, a dual mode of emplacement is suggested. Approximately 1 mile W of the gorge this facies appears to be identical to the lower landslide (with the exception of clast composition), thus indicating a similar origin. Also at this locality, it is both underlain and overlain by distal alluvial-fan deposits. The higher sand content of the matrix and stratigraphic position within, as well as deformation of, the turbidite facies at and just E of the gorge suggest subaqueous deposition, perhaps a mechanism similar to debris flow (Middleton and Hampton, 1973). The catastrophic event represented by this deposit probably originated in a manner similar to the one described for the lower landslide, but upon reaching the marine environment, it incorporated sufficient water to transform the landslide into a debris flow.

At the time of this writing, the source of this slide is not known. Based on geometry, Robinson and Threet (1974) suggested that it was derived from the Vallecito Mountains to the W. However, the presence of marble clasts within the slide deposits points to an alternate source terrane. To the best of our knowledge, the only local occurrence of marble is in the basement complex of the Fish Creek Mountains to the N.

HISTORICAL RESUME

The lower stratigraphic sequence, which is comprised of the braided-stream, alluvial-fan, and landslide facies, marks the initial sedimentation in the Split Mountain region. The braided-stream facies represents an alluviated valley occupied by northward-sloping braided channels, with the major source terrane being the plutonic basement of the Fish Creek and Vallecito Mountains. In addition, detritus was shed from the Miocene Alverson volcanic rocks in the southern Fish Creek Mountains and the more distant Peninsular Ranges to the S. A debris-flow dominated alluvial fan accumulated along the tectonically active western margin of the alluviated valley and eventually prograded well into the valley. A catastrophic landslide subsequently covered at least part of the alluvial fan surface and probably denoted the beginning of major tectonic adjustments.

With the incursion of the Gulf of California in Early Pliocene time, deposition of a paralic-to-marine unit succeeded the nonmarine deposits at Split Mountain, and accumulated in a southeastward deepening basin. A lagoonal environment to the NE was the site of evaporite precipitation of the Fish Creek Gypsum. While alluvial fans built into the basin from the N and W, turbidites accumulated around their submarine fringes and muds were deposited in the deepest parts of the basin to the SE. Emplacement of the upper landslide-debris flow temporarily interrupted the turbidite deposition and probably modified basin topography locally.

Chapter 12

STRUCTURE SECTION ACROSS THE SAN ANDREAS FAULT ZONE, MECCA HILLS

by

Arthur G. Sylvester and R. R. Smith*

ABSTRACT

The Mecca Hills lie on the northeast margin of the Salton Trough and consist of pre-Cenozoic crystalline basement rocks overlain by Late Cenozoic nonmarine sedimentary rocks. Two parallel, northwest-trending fault segments of the San Andreas fault system subdivide the area into three structurally distinct domains: a relatively undeformed marginal platform on the northeast; a folded and faulted zone 1.5 km wide between the two faults; and an inferred basin block to the southwest. The faults are high-angle, nearly planar structures that locally flatten abruptly upward into low-angle thrusts which carry slices of sedimentary rocks short distances on to the platform and basin blocks. Associated folds trend west-northwest, oblique to the faults and in a step-right en echelon arrangement. Where exposed in the central block, the basement-sediment interface is also folded. Basement in the anticlinal cores is pervasively fractured and appears to have adjusted cataclastically to contractional strain, whereas the sedimentary mantle folded passively in response to deformation at the basement level. The details of these structures are best observed in Painted Canyon which offers a relatively deep structural profile across the faults and the three structural domains.

*Address: c/o Shell Oil Company
Houston, Texas, 77001

INTRODUCTION

The Mecca Hills offer some of the best exposures and examples of the tectonic geometry related to the southern San Andreas fault zone, because structural and topographic relief is relatively high, and there is little or no vegetation and alluvial cover.

This chapter focuses upon Painted Canyon in the center of the area where the deepest and most representative structural profile can be conveniently studied. This description is based upon previous studies by Dibblee (1954), Hays (1957), Ware (1958), and Sylvester and Smith (1976).

STRUCTURAL AND LITHOLOGIC OVERVIEW

Structure

Four nearly vertical, northwest-striking faults are exposed in Painted Canyon or adjacent canyons. From northeast to southwest, these are: the Platform fault, the Painted Canyon fault, the Skeleton Canyon fault, and the main, most recently active trace of the San Andreas fault (Figs.23 and 24). For the purposes of this report the Skeleton Canyon fault is considered to be a strand of the San Andreas fault. All but the Platform fault branch upward and flatten abruptly into low-angle thrust faults. The Painted Canyon and San Andreas faults subdivide the area into two tectonic domains or blocks that are distinguished mainly by the style and degree of deformation, but also by the type and thickness of the mantle of Cenozoic sedimentary rocks. As shown in Figs. 23 and 26, the block northeast of the Painted Canyon fault is informally called the platform block; that between the San Andreas and Painted Canyon faults is the central block. A third domain, the basin block, is inferred beneath a thick cover of alluvium southwest of the San Andreas fault. The structural and lithologic contrasts among the three domains are summarized in Table 1.

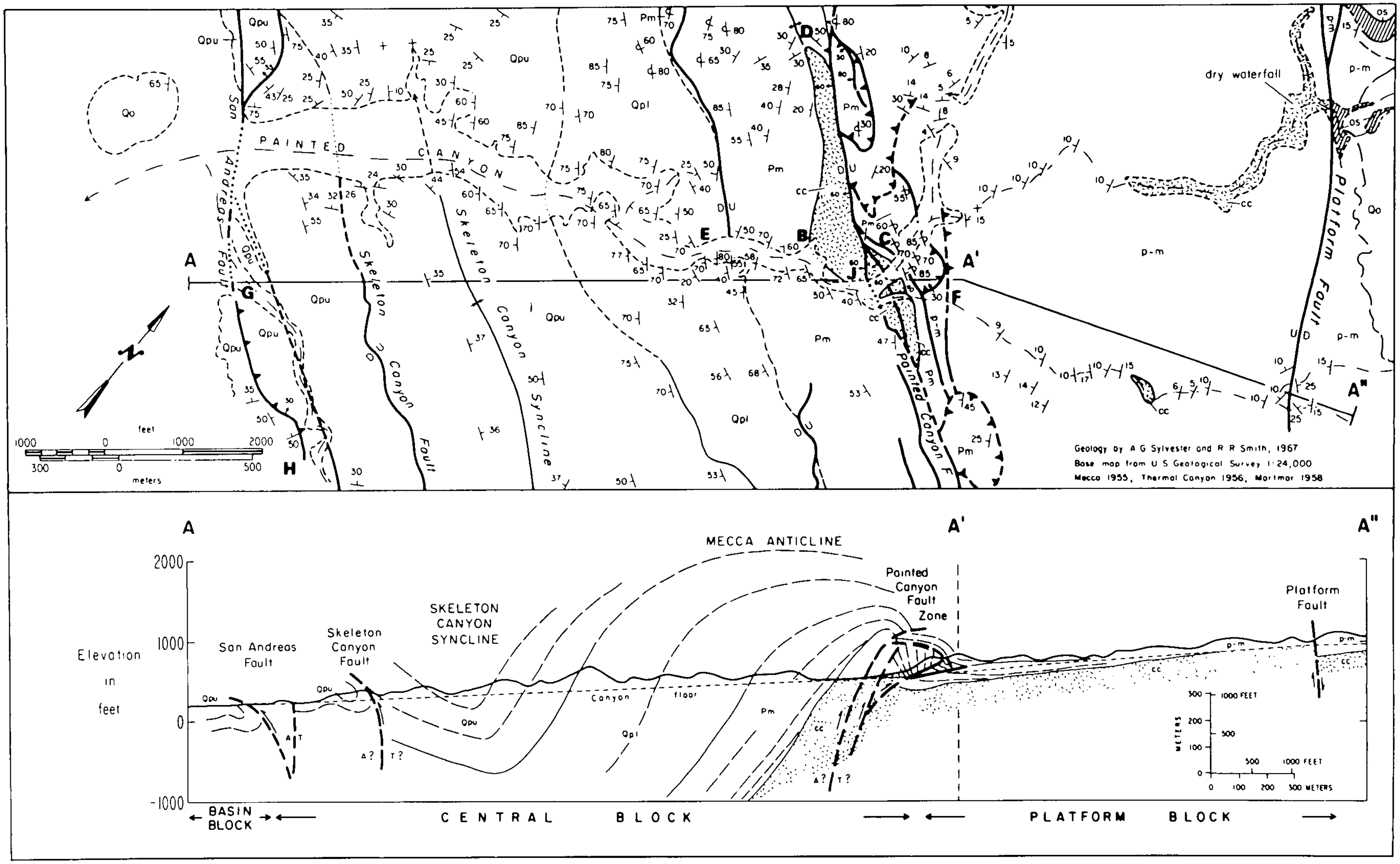

Fig. 23. Geologic map and structural profile of Painted Canyon, Mecca Hills. Symbols (oldest to youngest): Chuckawalla Complex (cc); Orocopia Schist (os); Mecca Formation (Pm); Palm Spring Formation (Qpl, lower member; Qpu, upper member); Palm Spring and Mecca Formations, undifferentiated (p-m); Canebrake-Ocotillo Conglomerate, undifferentiated (Qo).

Table 1
LITHOLOGIC AND STRUCTURAL CONTRASTS AMONG THE THREE STRUCTURAL BLOCKS OF THE 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 steeply tilted to the southwest	Basement-sediment surface gently inclined to southwest
	Cenozoic Sedimentary Rocks	
Alluvium	Arkose and conglomeratic arkose	Conglomeratic arkose and conglomerate
Thickness: 3000-5000 m (12,000-15,000 feet)	Thicker stratigraphic sequence than in eastern block (approximately 1750 m (5000 feet)	Relatively thin stratigraphic sequence (<750 m; <2000 feet).
Structure of sediments 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 slightly oblique to fault trends
	Steep west-trending normal cross faults	Steep-to-gently inclined northwest-trending normal faults

Table 2
THICKNESSES, AGES, AND LITHOLOGY OF CENOZOIC FORMATIONS IN THE MECCA HILLS (after Dibblee, 1954)

Formation	Lithology
Canebrake-Ocotillo Conglomerate (Pleistocene) 0-750 m (0-5000 feet)	Gray conglomerate of granitic debris in central Mecca Hills, reddish conglomerate of schist in eastern Mecca Hills.
Palm Spring Formation (Pliocene (?) and Pleistocene) 0-1200 m (0-4800 feet)	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 grey green siltstone.
Mecca Formation (Pliocene) 0-225 m (0-800 feet)	Reddish arkose, conglomerate, claystone; chiefly metamorphic debris in basal strata.

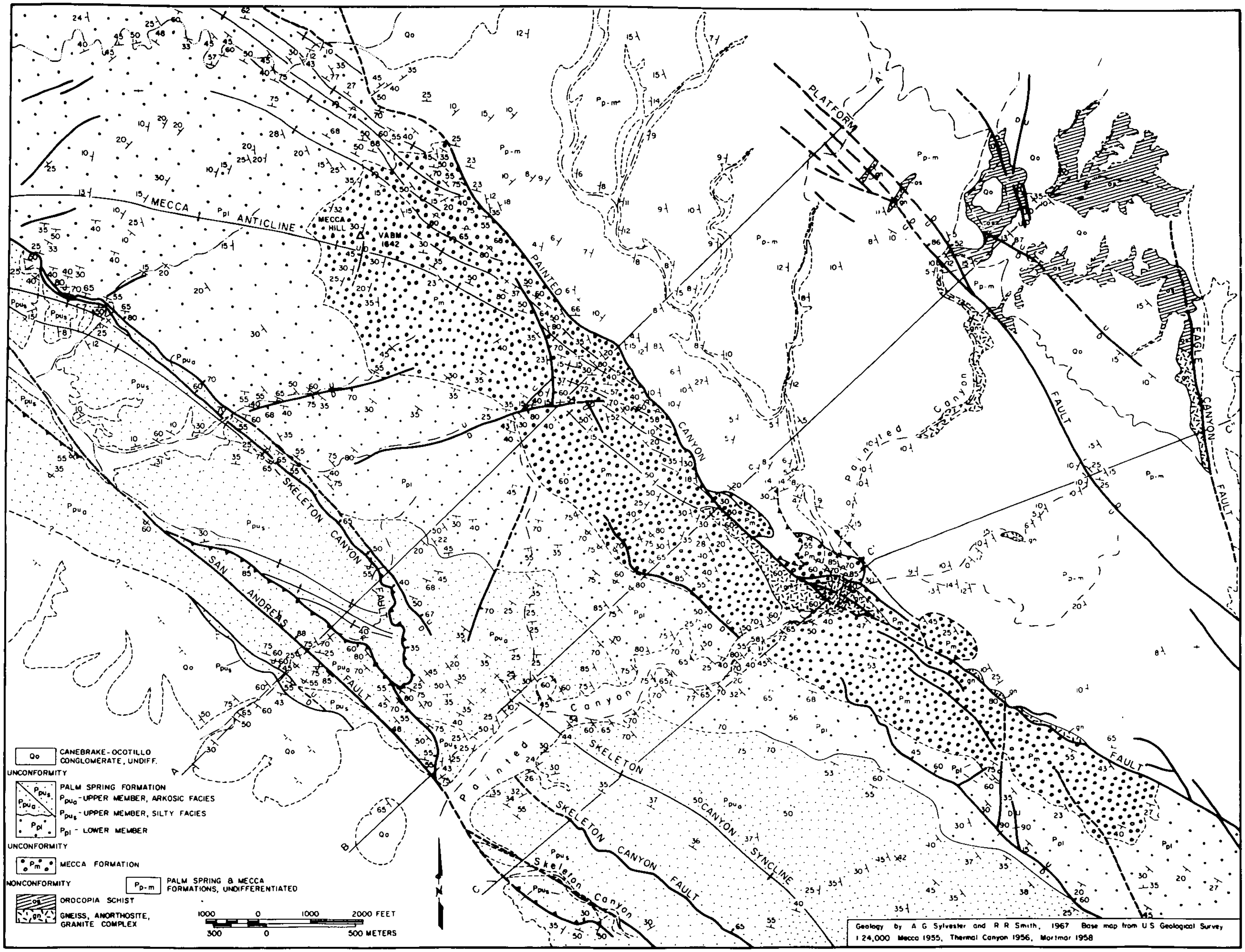

Fig. 24. Geologic map of the central Mecca Hills (Sylvester and Smith, 1976). AA', BB', CC' are locations of cross-sections shown in Fig. 25. Reproduced with permission of American Association of Petroleum Geologists.

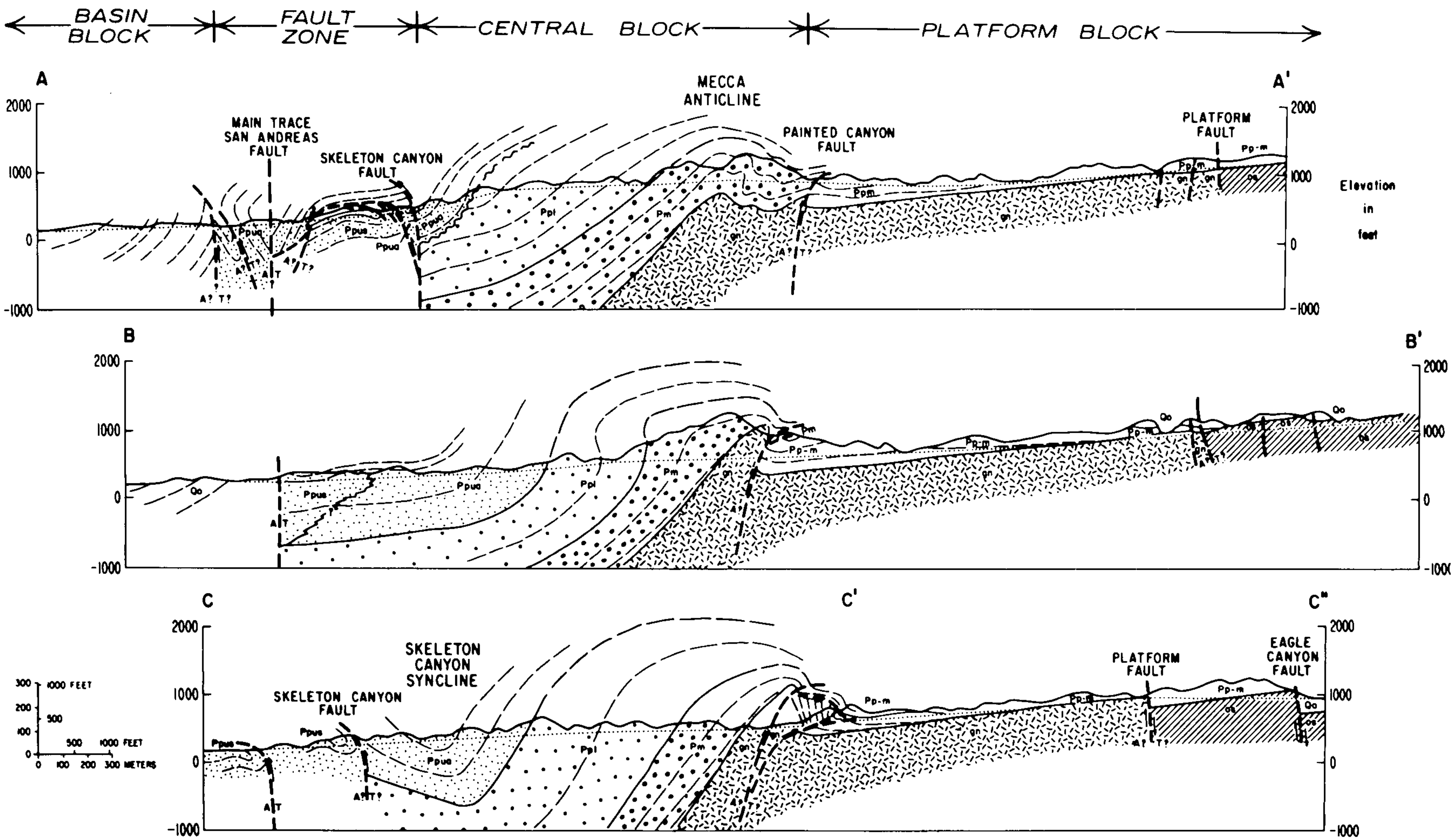

Fig. 25. Structural cross-sections of central Mecca Hills (Sylvester and Smith, 1976). See Fig. 24 for locations of cross-section lines. Reproduced by permission of American Association of Petroleum Geologists.

BASEMENT

The basement is comprised of two main rock units: (1) the Chuckawalla Complex (Miller, 1944), which is chiefly Precambrian 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, 1968). The Chuckawalla Complex is thrust upon the Orocopia Schist in the Orocopia Mountains (Crowell, 1962, 1975b), but in the Mecca Hills, the two rock units are separated by the high-angle Platform fault (Fig. 23) and Eagle Canyon fault (Hays, 1957) whose displacements are not well-documented.

CENOZOIC STRATIGRAPHY

Late Tertiary and Quaternary nonmarine sedimentary rocks (Table 2), including intercalated alluvial fan, braided stream, and lacustrine deposits, rest unconformably upon the basement. Stratigraphic thicknesses, age relationships 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 gross nature of the stratified sequence, however, records a period of continental 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 as it is today.

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

The Palm Spring Formation (Table 2) appears to mark 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 Mecca pediment to the east. Like the Mecca Formation, the Palm Spring

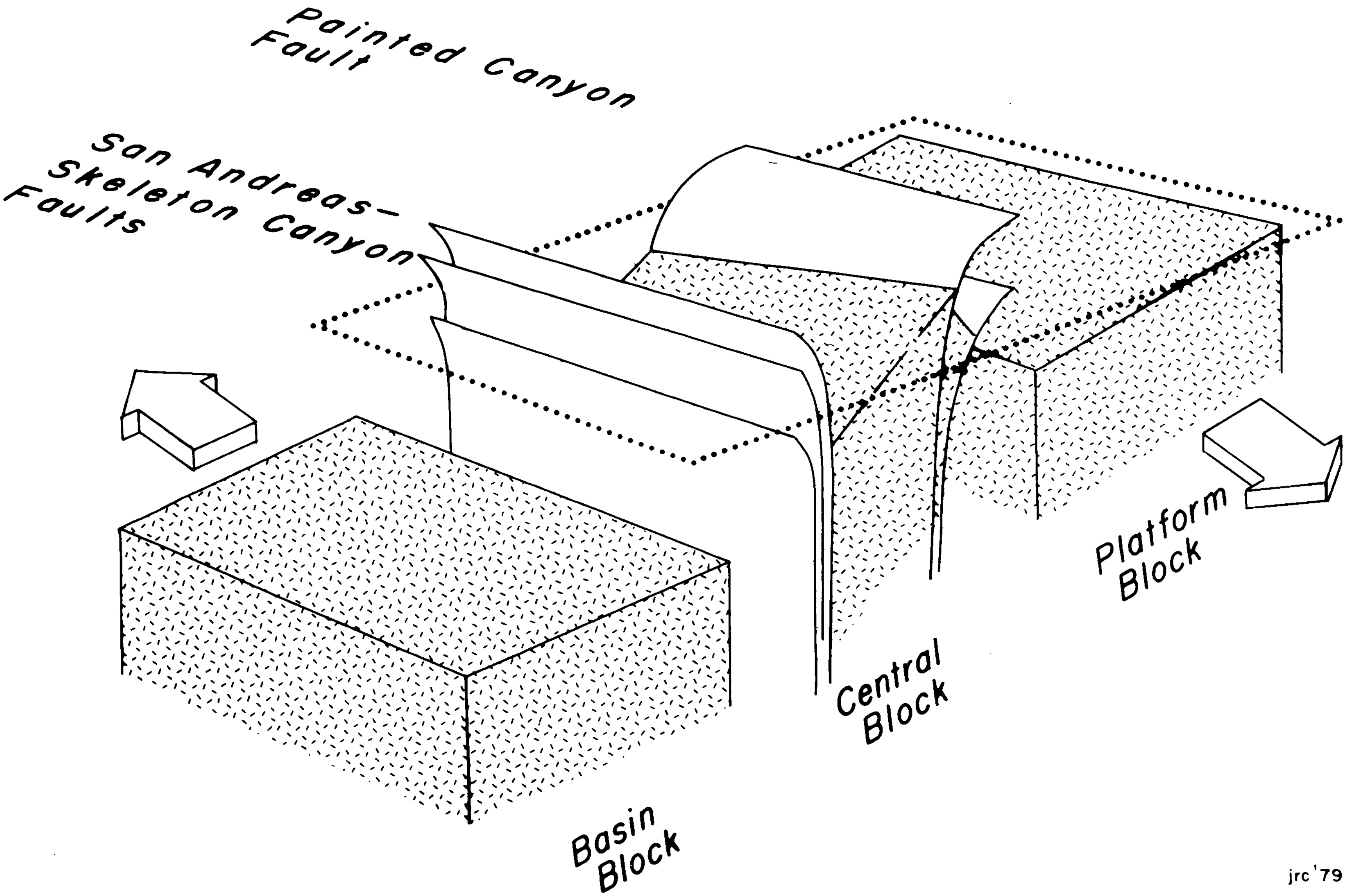

Fig. 26. Idealized block diagram of basement and principal faults in the central Mecca Hills. Dotted parallelogram represents ground surface. Non-parallel arrows indicate relative convergent right oblique-slip of basin and platform blocks resulting in crustal shortening manifested by folding of sedimentary rocks and palm-tree geometry of the faults. Modified from Sylvester and Smith (1976).

Formation thickens abruptly across the Painted Canyon fault and is progressively finer-grained basinward. Numerous diastems within the formation southwest of Painted Canyon fault indicate depositional interruptions reflecting Plio-Pleistocene episodes of folding and faulting at the margin of Salton Trough.

STRUCTURAL PROFILE

Upper Painted Canyon

Platform Block. The upper part of Painted Canyon is incised into the northeastern tectonic domain: the platform block. Near the dry waterfall (Fig. 23) 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 prevents further access up the canyon by motor vehicle. It is cut into migmatite of the Chuckawalla Complex that is massive and unfractured in contrast to that in the central block. About 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 (Figs. 23, 24, and 25). Nearly horizontal slickensides show that the latest movement was horizontal, but drag folds with nearly horizontal axes indicate that a significant component of vertical separation has occurred as well.

The basement is overlain nonconformably by beds 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 5 m deep were incised and filled with 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, the Cenozoic sequence is undeformed in the platform block.

Central Painted Canyon

Central Block. The central block is a 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 (Fig. 24). North of Painted Canyon the axial traces of most folds trend about N70°W and define a step-right en echelon pattern in the central part of the block; near the edges of the block, 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 that comprises the topographically highest terrane northwest of Painted Canyon (Fig. 24). The slivers of basement exposed along the Painted Canyon fault represent the core and structurally deepest exposures of the anticline.

Painted Canyon probably received its name from the varicolored exposures of basement and overlying Mecca Formation in the central part of the canyon around localities B, J, and C (Fig. 23). Here dark migmatitic gneiss, intricately intruded by small, irregularly shaped bodies of white Mesozoic (?) granite and light orange and yellow felsite dikes (K-Ar age 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 is tilted 60° to the southwest. The contact and overlying beds are folded into a northwest-plunging 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, Figs. 23, 24, and 25). 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 J, is pervasively fractured and sheared into a granulated mass of rock fragments ranging typically from 0.5 to 5 cm in diameter. The degree of fracturing is highest next to the fault. The overlying sedimentary rocks, however, are strongly sheared only within a meter or so of the fault plane; the basement-sediment contact is not a plane of slip. These field observations are interpreted as showing that in response to contractional strain, the basement adjusted cataclastically by slip on old fractures and shear planes that are assumed to have 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 on thin claystone and mudstone beds. The mechanism might be analogous to passive warping of a pliable material over a constrained and deformed mass of buckshot.

A small anticline and syncline are prominently exposed in the northwest wall of Painted Canyon at locality E (Fig. 23). They are relatively minor structures and are not shown on the map, because they die out vertically and laterally 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 northeast edge of the central block are interpreted as having formed in response to shortening of beds in the fold limb shared by the basement-cored anticline, described above, and the Skeleton Canyon syncline (Figs. 23, 24, and 25).

Painted Canyon Fault. The Painted Canyon fault is a major structural discontinuity at least 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 more steeply in canyon bottoms than on adjacent ridges, showing that it is concave downward in cross-section. Beneath the low-angle segments, footwall strata of the platform block are dragged abruptly to vertical and overturned attitudes. The magnitude and sense of slope are not known except for the pre-Mecca Formation vertical component which locally exceeds 150 m as determined from offset of the basement-Mecca Formation unconformity.

The geometry of Painted Canyon fault and its associated structures is displayed best in the walls of central Painted Canyon as shown diagrammatically in Fig. 27. The structure is essentially that of an overturned, faulted anticline in the hanging wall and an overturned syncline in the footwall. 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. 23). The structural evolution of these folds and faults is illustrated diagrammatically in Fig. 28. 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.

Lower Painted Canyon

The lower part of Painted Canyon, while still within the central block, is a structural depression in contrast to the

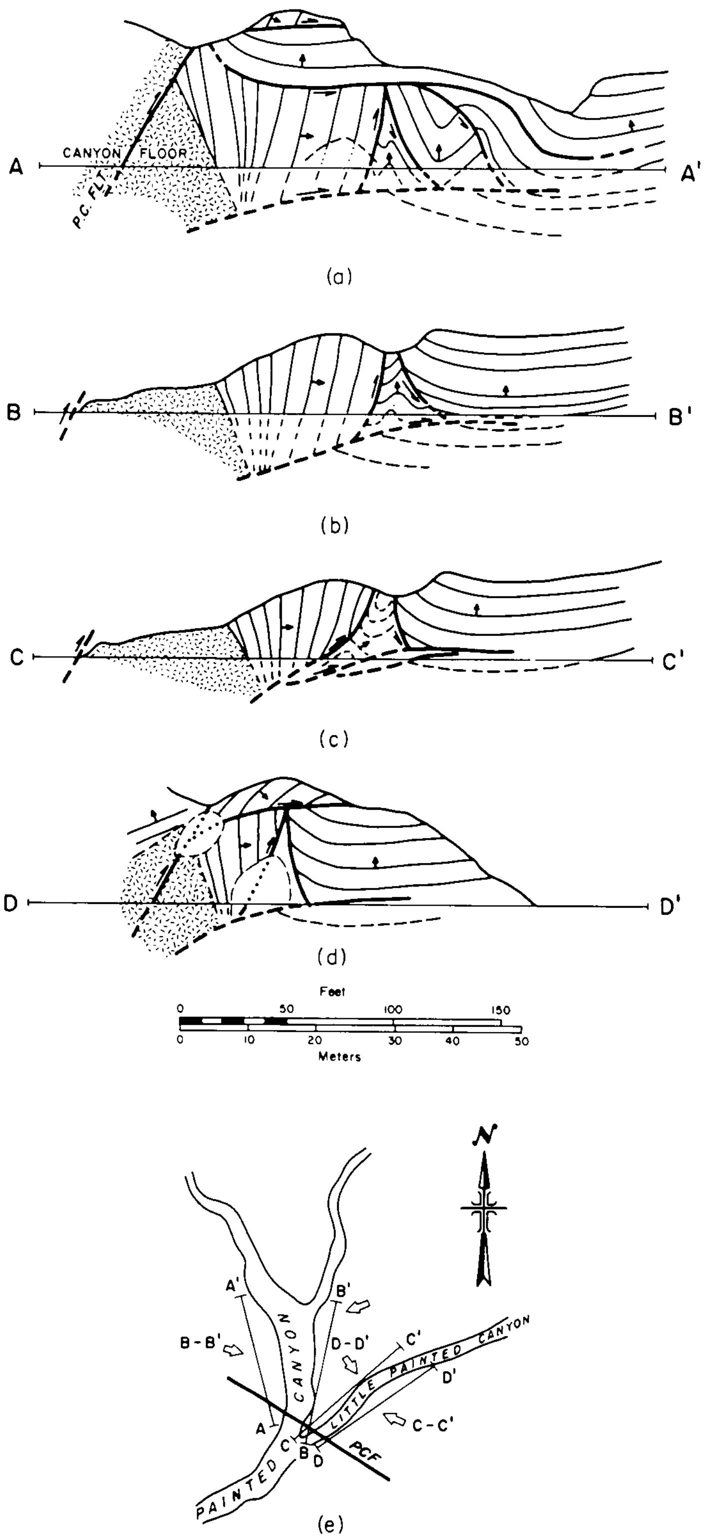

Fig. 27.

Generalized cross-sections of buckled beds 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 view points for cross-sections.

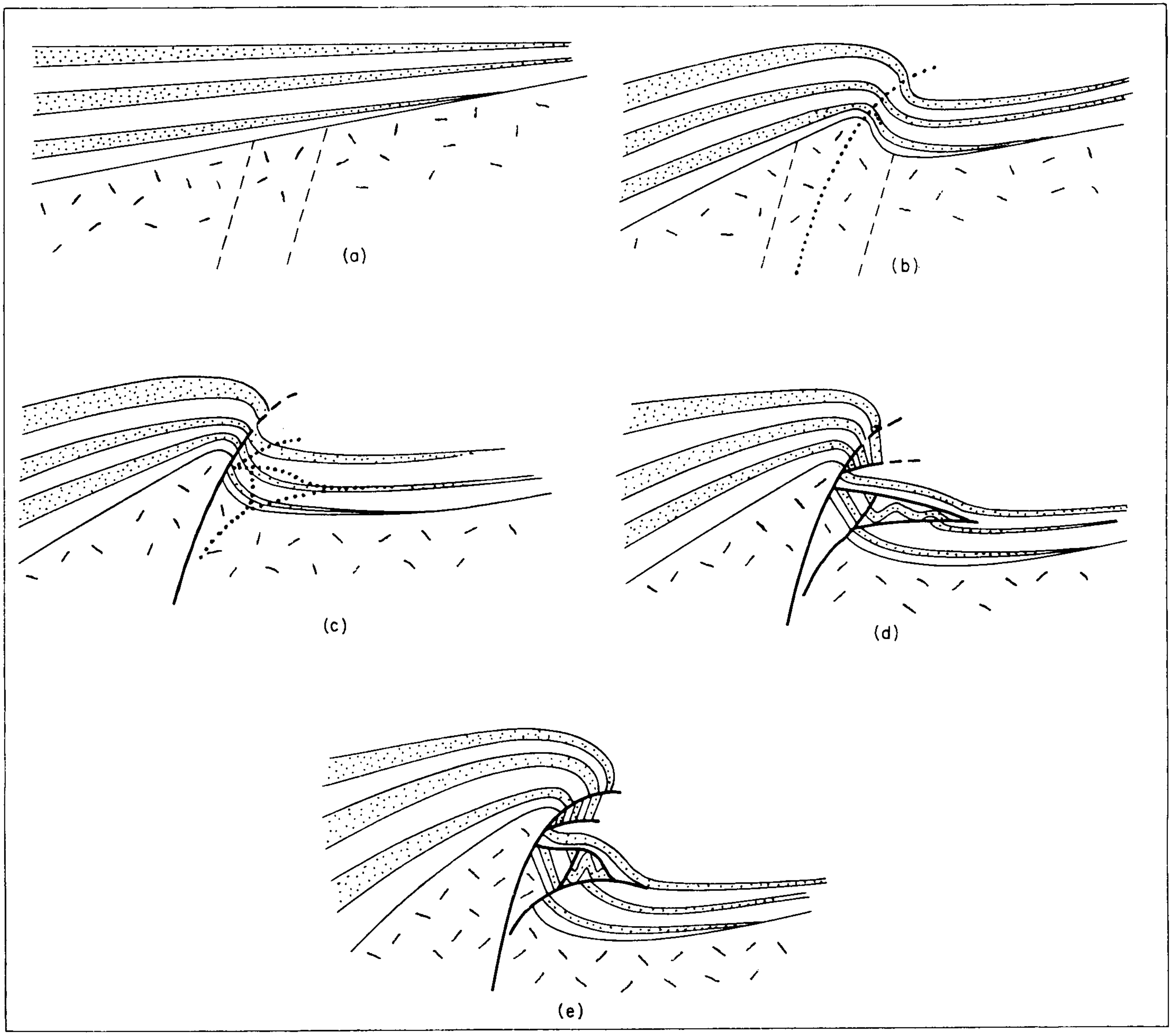

Fig. 28.

Postulated structural evolution of Painted Canyon fault. (a) Initial geometry of basement and overlying sedimentary strata; (b) Flexure of basement by movement along closely spaced fractures and shears within zone indicated by dashed lines; (c) Rupture of basement along Painted Canyon fault; (d) Secondary faulting in syncline, incipient buckling of beds in footwall block; (e) Continued right oblique displacement on Painted Canyon fault, rotation of secondary faults, and continued buckling of strata in footwall block. After Sylvester and Smith (1976); reproduced by permission of American Association of Petroleum Geologists.

structural culmination where the basement is exposed against the Painted Canyon fault. As one proceeds down the canyon, he rises up-section stratigraphically from the Mecca Formation, through the lower and upper members, respectively, of the Palm Spring Formation (Table 2, Figs. 23 and 24).

The lower member of the Palm Spring Formation dips steeply down-canyon as part of the southern and locally overturned flank of Mecca Anticline. Gently folded and undulating strata in the upper member of the Palm Spring Formation nearer the mouth of the canyon connect with more tightly appressed folds northwest and southeast of the canyon.

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). The faults are convex-upward in cross-section and steepen with depth. Locally, tight and nearly vertical folds occur beneath low-angle segments of the gouge zones, such as at locality H. There arkosic sandstones and interbedded siltstones of the upper Palm Spring Formation are strongly folded into steeply-plunging open folds in the core of an overturned syncline beneath a northeast-dipping thrust segment of the San Andreas fault.

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

Basin Block

Geophysical studies by Biehler (1964) and Biehler, Kovach and Allen (1964) indicate that the depth to basement ranges from 2000 m to as much as 5000 m beneath Coachella Valley. A steep gravity gradient across the San Andreas fault in the Mecca Hills area probably indicates a near-vertical step of the basement-sediment interface of at least 4000 m (Fig. 9). 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.

ACKNOWLEDGMENTS

Previous versions of the manuscript were reviewed by R. V. Sharp and J. C. Crowell. The Shell Development Company (Houston, Texas) supported the study and granted permission to publish this guide. An earlier version of this guide was published by Sylvester and Smith (1975).

Chapter 13

EXCURSION GUIDE

San Diego to Palm Springs, California

by

John C. Crowell and Arthur G. Sylvester

INTRODUCTION

In the paragraphs below are brief comments concerning geologic features on the three-day field trip from San Diego, ending at Palm Springs, California. Although emphasis is upon tectonics and especially Late Cenozoic tectonics, many different types of geologic and geophysical data are pertinent. Moreover, because the region of the San Andreas-Salton Trough juncture is now active and evolving, geomorphic and neotectonic observations and inferences are especially significant.

SAN DIEGO TO DANA POINT

Take Interstate 5 from San Diego N to Capistrano Beach (about 57 mi) and the Highway 1 turnoff. At the traffic light turn seaward into Dana Point Marina and drive across arched bridge to turnaround at the NW end of the inside marine breakwater. Parking for buses is available here, but with some difficulty if there are many cars already parked. There are green grass, picnic tables with shade, drinking water, and toilets.

Our route N from the San Diego estuary first follows along the course of the Rose Canyon fault, a branch of the Newport-Inglewood fault zone, and then along the coast, with Pleistocene marine terraces overlying unconformably marine Eocene beds. These beds thicken westward and were formed at a shelf margin (Lohmar and Warme, 1979) within a forearc basin. Channels containing conglomerate show that their sources lay to the E and NE across the present Peninsular Ranges (Kennedy and Moore, 1971; Howell and Link, 1979) and included some that are now offset by the San Andreas fault system.

STOP: DANA POINT

Strata exposed in the cliff along the N side of Dana Point Harbor, as shown in the diagram (Fig. 29), include San Onofre Breccia on the W, faulted against Upper Miocene and Pliocene Capistrano Formation on the E. Details of three submarine channels filled with conglomerate and sandstone are especially well exposed.

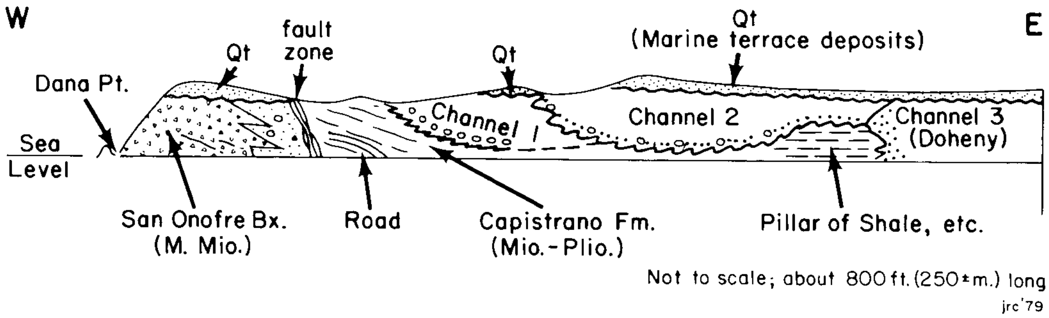

Fig. 29. Sketch of geologic relations in the sea cliff bordering Dana Cove. Refer to text for explanation.

The marine San Onofre Breccia accumulated at the base of steep escarpments interpreted as fault scarps. Debris flows and alluvial fans extended eastward from this scarp, consisting mainly of material from Catalina Schist, the basement terrane underlying part of the region now under the Pacific Ocean on the W, and exposed on Catalina Island and in the Palos Verdes Hills and recovered from a number of wells and dredgings (Howell, ed., 1976). Blueschist (including glaucophane), greenschist, amphibolite, gabbro, are among the rock types represented as clasts. San Onofre Breccia documents an episode of mid-Miocene deformation that apparently included faulting with marked vertical separations. Aspects of these tectonic events may be comparable to those we will observe onshore in southern California, especially in the Salton Trough.

The submarine channels, now filled with sandstone and conglomerate, flowed toward the SE and are interpreted as scoured within the near-contemporaneous Capistrano Formation by bottom currents leading from the shoreline of the Los Angeles basin into deep water (Bartow, 1966, 1971; Normark and Piper, 1969). Coarse rip-up breccias, where clasts of Miocene shale are embedded in coarse sandstone, and overhanging walls of channels, are exposed in the cliff face. Nested submarine fan-channels are also present about 10 km (6 mi) to the SE (Walker, 1975).

DANA POINT TO ELSINORE OVERLOOK

From Dana Point retrace route to Interstate 5, turning toward Los Angeles, and driving about 4 mi to San Juan Capistrano and the turnoff on the Ortega Highway (Hwy 74). Drive northeastward about 20 mi through the Santa Ana Mountains to overlook with stone wall on the left (NE) side of highway, beyond the range crest. The overlook is about a mile beyond El Cariso Forest Station, and just around the corner from paddle post 7.32. Be careful upon entering the overlook parking area because of partially obstructed visibility of on-coming traffic.

Rock exposures are poor between San Juan Capistrano and the basement terrane of the Santa Ana Mountains. The stratigraphic section here dips gently toward the SW and consists primarily of Cretaceous, Eocene and Miocene strata. Thus, the route of the excursion proceeds downsection from Miocene strata to pre-Cretaceous crystalline basement rocks. The Cretaceous and Eocene beds are interpreted as part of a forearc-basin sequence, now broken by younger faults and locally folded as well as tilted. Middle and Late Miocene strata, assigned to the Monterey Formation, crop out near San Juan Capistrano and for the first 4 mi or so along Hwy 74. These beds, consisting largely of siliceous shale with intercalated sandstone, were laid down offshore in a basin formed during plate-margin fragmentation when the Pacific lithospheric plate met the North American plate. The Cristianitos fault, which we cross at the contact between Miocene and Eocene strata, has a NNW strike and is interpreted as having played a role in the formation of the Los Angeles basin in Miocene time. This fault is parallel to other faults in the San Joaquin Hills, W of San Juan Capistrano, that are intruded by Middle Miocene volcanic rocks. They are therefore somewhat older than later stretching of the basin floor when the lava was intruded.

E of the Cristianitos fault the Eocene Santiago Formation is first exposed, consisting of about 3200 ft (975 m) of marine buff sandstone with interbedded dark siltstone (Fife, 1972). Beneath this formation in the region lies the Paleocene Silverado Formation with a thickness that ranges between 700 and 1500 ft (215-460 m), but it is not exposed along Hwy 74. The formation is characterized by distinctive units near its base, including claystone, lignite and sub-bituminous coal beds. These nonmarine units grade upward into marine sandstone and siltstone, and were laid down in a coastal belt at the margin of a deeply weathered terrane with humid climate (Sage, 1973a). Inasmuch as this shoreline belt of distinct facies is repeated in the Elsinore Trough, right slip of about 40 km (24 mi) is suggested (Lamar, 1953; Sage, 1973a, b), but discrete geological lines with their piercing points with the Elsinore fault have not yet been identified with certainty (Fig. 5) (Crowell, 1962).

The Paleocene beds along Hyw 74 are faulted against marine Cretaceous strata assigned to the Williams and Ladd Formations, units much better exposed in the northern Santa Ana Mountains. Outcrops in the hills W of Hwy 74, visible from the bus, consist mainly of gently SW-dipping thick buff sandstone with interbedded thin siltstone. The marine Cretaceous section in this region grades downward into the nonmarine Trabuco Conglomerate that in turn lies nonconformably upon the basement complex of the Santa Ana Mountains. This formation, composed of coarse red-brown conglomerate, crops out for about a mile along the highway beyond the bridge over San Juan Creek where the road follows along the NW side of the canyon. Stone types and imbrications show that the conglomerate was derived from basement terrane exposed onward to the E.

The basement complex below the Upper Cretaceous Trabuco Conglomerate first consists of Santiago Peak volcanic rocks composed of interbedded rhyolite, andesite, diabase, and tuffaceous breccias that have been weakly metamorphosed (Sylvester and Bonkowski, Chap. 7, this volume). Along our route these exposures are succeeded by those of the Southern California batholith consisting of gabbro, tonalite, granodiorite, quartz monzonite, and related dikes and veins (Sylvester and Bonkowski, Chap. 7, this volume). Isotopic ages based on Rb-Sr and U-Pb methods for these granitic rocks range from 135 to 95 m.y. (Banks and Silver, 1969; Krummenacher and others, 1975). K-Ar apparent ages range between 115 m.y. and 50 m.y., with a gradient from SW to NE from older to younger (Krummenacher and others, 1975). Near the summit of Hwy 74, the hillsides south of the highway are littered with light-colored exfoliation boulders of granodiorite; north of the highway are scattered boulders of gray (Bonsall) tonalite, distinguished from most other granitoids of the Southern California batholith by the presence of abundant well-oriented inclusions of gabbro, metavolcanic and metasedimentary rocks.

STOP: LAKE ELSINORE OVERLOOK

From the walled parking area and overlook, we look down on

Lake Elsinore, the rectangular alluviated area around it, and the Perris Peneplain beyond to the NE. The lake is the main tourist attraction in the area, but in the early days Elsinore was known for its mineralized hot springs and resorts. Many hot springs issued along the NE side of the lake prior to 1890, but an irrigation canal disrupted the water table and now hot water is obtained only from wells. The City of Elsinore utilized water from thermal wells until a few years ago when 5 ppm fluoride was found in the water, an amount equal to more than five times the recommended limit. The lake is presently filled with water imported by aqueduct from the Colorado River and from runoff from the San Jacinto River.

The lake basin is bounded by a rectangular arrangement of active faults (Fig. 30), which are easily distinguished from the overlook by their prominent scarps, and which together constitute a pull-apart depression under right slip between two main en echelon strands of the Elsinore fault system: the Glen Ivy and Willard faults. In this arrangement, the Lucerne fault at the NW end of the lake and the N-striking unnamed fault at the SE end of the lake are dip-slip faults. About 6 km (4 mi) of slip is suggested by the size and shape of the alluviated depression, if the pull-apart is closed up and allowance is made for some crustal stretching and sagging.

Note that there is a smaller en echelon side-stepping of the fault zone to the NW (Fig. 30), resulting in what is probably another pull-apart. Although vertical separations here are great, and probably amount to several kilometers, the right-slip component may amount to very much more (Crowell and Ramirez, Chap. 3, this volume). If the total right slip on the fault zone is indeed as much as the 40 km (25 mi) suggested by the offset Paleocene shoreline facies, the slip required for the Elsinore pull-apart must be a partial slip only, and therefore considerably younger. Confirmation of these interpretations has not yet been made by finding offset geological lines (or strike separation of near-vertical basement contacts).

The kinematic mechanism responsible for the Elsinore pull-apart is inferred to be quite similar to that taking place within the Salton Trough. We have included this stop to observe the geometry of such a feature on a relatively small scale, to appreciate the relations between separation and slip on a strike-slip zone, and to note as well the relations between tectonics and sedimentation. In a flexible crust, such as that envisioned for this region, terrain is arched up at places and stretched and depressed at others within a transform-fault regime.

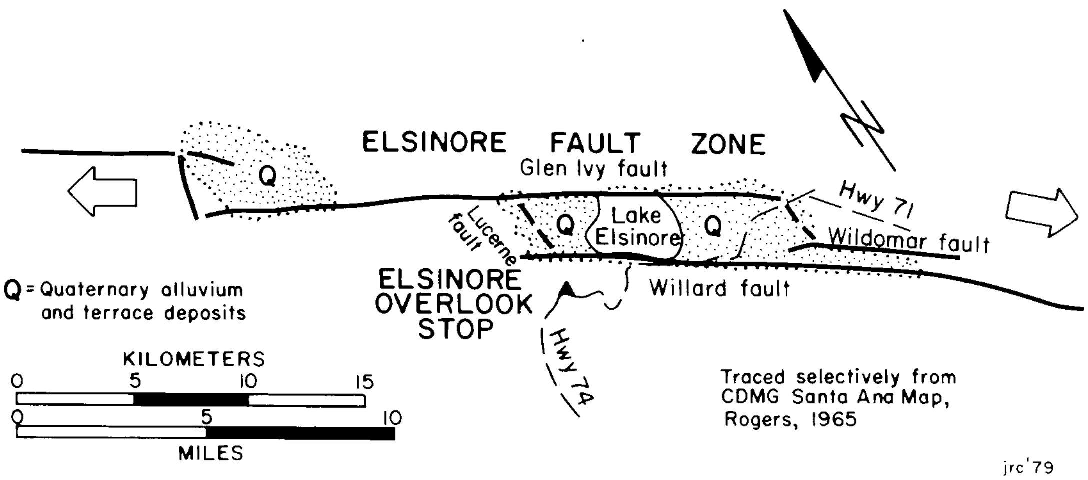

Fig. 30. Sketch map of Lake Elsinore region showing right-stepping of strands of the Elsinore fault zone and depressions inferred to form at the pull-apart junctures.

ELSINORE OVERLOOK TO SALTON TROUGH OVERLOOK

Continue downgrade along Hwy 74 to Lake Elsinore, turning SE on Grand Avenue and driving on it for 5 mi through Lakeland Village, to Corydon Dr. Turn NE on Corydon Dr. along edge of the airport, making a few jogs, to Hwy 71 (Temp. I-15), then SE to Temecula-Rancho California area, and east on Hwy 79, through the hamlets of Aguanga, Oak Grove, and Warner Springs. About 3.5 mi S of Warner Springs, turn SE on County Hwy S-2 for 4.6 mi and E on Hwy S-22 through the village of Ranchita and across the crest of the range. Wind down the grade, stopping at the wide turnout just around the corner from paddle post 12, about 5 mi E of the summit.

Roadcuts between the overlook and the floor of Elsinore Valley expose Bedford Canyon schist (Early Mesozoic) intruded by spheroidally weathered gabbro and tonalite characterized by abundant rounded inclusions.

Physiographic details of the Elsinore fault zone are easily observed along the SW edge of the Elsinore Valley (Weber, 1975). Hwy 74 goes over the Willard fault scarp about 1/2 mi before the junction with Grand Ave. Fissures are reported to have formed along this fault during the San Jacinto Earthquake of 1918 (Engel, 1959). Note the notched and faceted spurs at the base of the Santa Ana Mountains. Uplifted fault slices form a chain of discontinuous hills in the broad alluvial area SE of Lake Elsinore, where fault scarps border some of these low hills on both the SW and NE sides. We cross this zone of faulting on Corydon Rd. Additional fault features along the Elsinore zone are in view as we drive along it to Temecula and Rancho California. The Rainbow Canyon Golf Resort is located within the fault zone in the region where alluvium and terrace deposits have been disected and removed by the capture of inland drainage by the Santa Margarita River. This river, which flows into the Pacific Ocean along a direct course to the SW, has formed the deep Temecula Gorge, and is now capturing drainage NE of the Santa Ana Mountains and the Elsinore fault. The entry of this gorge lies W and adjacent to the freeway (I-15) at the Hwy 79 interchange.

Between the Elsinore fault and the Salton Trough overlook, we drive through the northern Peninsular Ranges, underlain by granitic and gneissic rocks of various types (Sylvester and Bonkowski, Chap. 7, this volume). The region is also transected by several NW-SE-striking fault zones, and our route takes us along the course of the Agua Caliente fault on our way to Warner Springs. Vertical separations along the faults of this zone show up in the topography and have helped form intermontane basins in which shallow alluvium has accumulated. The direction and amount of slip on these faults, however, is unknown because the basement terrane has yet not been investigated in sufficient detail to establish correlations across them. Their strike and pattern suggests, however, that they are mainly right-slip faults with variable vertical separations. Hot springs, such as those at Warner Springs, are present along the aptly named Agua Caliente fault zone.

Alluvium consisting of disintegrated granitic debris (grus) makes up much of the sedimentary fill in several of the small basins crossed along our route. At places these deposits are undergoing disection so that unconformable contacts, including buttress unconformities, are exposed in highway cuts. In fact, the whole region constitutes a veritable sand-grain factory. Deep weathering breaks down the basement gneisses and granitic rocks to disaggregated grains which in time make their way through a succession of continental basins and temporary resting places to the beaches and to the sea. In Miocene and Pliocene times such regions surrounded the Los Angeles basin, as well as several basins in the near offshore, and provided ideal sources for the sand within turbidity currents. These currents carried sand into deep-basin fans, channels, and sheets that now form the reservoir rocks for many of the prolific oil fields, especially those in Late Miocene and Pliocene strata of the Los Angeles basin and environs.

STOP: SALTON TROUGH OVERLOOK

View eastward into the Salton Trough with Borrego Valley in the foreground. Note the fault-controlled topography, the granitic and gneissic rocks of the Peninsular Ranges basement in the vicinity, and the sedimentation pattern now prevailing in the trough below. Stream courses into the Borrego Valley are much shorter and steeper than those flowing westward into the Pacific Ocean behind us. Distally the large alluvial fans grade into playa deposits. With good visibility we can see beyond the Salton Sea to the crest of the Chocolate Mountains, about 96 km (60 mi) due E. The Salton Trough or graben is complex, and its width between the marginal rims at this latitude is about 100 km (62 mi). Faults with vertical separations, including those with normal slip, are in part responsible for the difference in topographic relief in the vicinity of the overlook. For example, aligned notches in the basement terrane below us to the SE are along a fault, but one within apparently homogeneous granite. Some of these faults are interpreted as related to collapse under gravity as the graben widened, but others may be related to the formation of the proto-Gulf of California (Crowell and Ramirez, Chap. 3, this volume), or even older basin-range faulting.

Displacements along braided strands of the San Jacinto fault zone are largely responsible for the topography within the Borrego Valley and at its NW and SE margins. Note the faceted spurs along the Coyote Creek fault and beyond Clark Valley along the SW face of the Santa Rosa Mountains. Alluvium, folded into a complex broad arch, constitutes the Borrego Badlands lying SE of the plunging end of Coyote Mountain. Borrego Mountain lies in turn along trend farther SE. Structural details in this region were mapped and studied intensively following the Borrego Mountain Earthquake of April 9, 1968 (magnitude 6.4) (Sharp and many others, 1972). Many of these structural details fit a simple-shear scheme (Crowell and Ramirez, Chap. 3, this volume).

SALTON TROUGH OVERLOOK TO SPLIT MOUNTAIN GORGE

Continue downgrade into the town of Borrego Springs, turning S at the roundabout onto Borrego Springs Rd. Travel for about 10 mi to intersection with Hwy 78 and proceed E for about 6.5 mi to Ocotillo Wells, then S on Split Mountain Rd. for 7.4 mi to the crossing of Fish Creek Wash. Drive up the wash to the vicinity of the Fish Creek Campground along unimproved tracks. Most vehicles can drive all the way through the Split Mountain Gorge; busses may need to park near the campground (about 0.6 mi from the paved Split Mountain Rd.). The geology within the gorge is best observed on foot (Kerr, Pappajohn and Peterson, Chap. 11, this volume).

In driving across Borrego Valley, note the pattern of the fan sedimentation. Older fan surfaces were arched along the general trend of the San Jacinto fault zone to block drainage and so form a depression now occupied by the Borrego Sink. Fanglomerate, overlying unconformably tilted similar strata, is exposed in the steep walls of San Felipe Creek where the highway crosses it. Elongate hills, such as Borrego Mountain and those SE of Ocotillo Wells, are interpreted as anticlines, up-tilted blocks, and squeeze-ups within the San Jacinto fault zone. The linear margins of the Ocotillo Badlands and Halfhill are fault-controlled, and the depression occupied by Halfhill Dry Lake probably owes its origin to a combination of tectonic blocking of drainage by these hills and to the building out toward the NE of the broad Fish Creek fan.

STOP: SPLIT MOUNTAIN GORGE

Walk into the gorge to observe debris-flow deposits and fanglomerates deposited at the margin of the basin in Miocene time. The stratigraphic section here is described in Kerr, Pappajohn and Peterson (Chap. 11, this volume).

SPLIT MOUNTAIN GORGE TO SALTON SEA OVERLOOK

Retrace route to corner of Yaqui Pass Rd. and Borrego Springs Rd. (a Chevron service station is on the NW corner). Turn N for 0.5 mi, then curve W and N again on Borrego Valley Rd. to Palm Canyon Dr., and E along Hwy S-22 and through two right-angle bends. To reach the optional Fonts Point Stop, drive 3.1 mi E of Pegleg Smith Monument to marked gravel road. Fonts Point is 4 mi S along a road inadvisable for large busses. Salton Sea overlook is about 12 mi E of Fonts Point turnoff, and 3 mi E of a tall microwave tower and the San Diego-Imperial County line. Park in a broad flat next to the highway on the S above an arroyo.

Our route takes us around the S end of Coyote Mountain and across buried strands of the San Jacinto fault zone. Rocks in Coyote Mountain include the Santa Rosa mylonite (Sharp, 1967, 1979; Theodore, 1966, 1970; Sylvester and Bonkowski, Chap. 7, this volume), a tectonic-movement zone of Late Cretaceous age that has been displaced by Late Cenozoic faults. The Santa Rosa mylonite belt extends from Palm Springs southeastward through the Santa Rosa Mountains to the tip near where we pass it on Hwy S-22. It is also present within the San Jacinto fault zone at Coyote Mountain, most of Borrego Springs, and on southward into the eastern Peninsular Ranges. The zone consists of pervasively sheared cataclastic rocks of mid-Cretaceous and older basement types, deformed under ductile conditions at depths estimated between 11-23 km and temperatures approaching the minimum melting temperature of granite (650°-700°C) (Theodore, 1970). The thickness of the mylonitic zone as now known reaches 8 km S of Indio. It is associated at many places with gently cross-cutting thrust faults with NE dips, inferred to be only slightly younger than the mylonitization. At places these thrust faults have been reactivated with normal-slip where they have provided sites for faulting in connection with the formation of the Salton Trough. The movement zone, now deeply eroded, is probably a manifestation of events when a convergent plate boundary existed in western North America.

In traveling eastward from the tip of Coyote Mountain, note the depression occupied by Clark Lake and the gentle swell of the Borrego Badlands consisting of Upper Cenozoic sediments deformed and arched along the trend of the San Jacinto fault zone. Clark Valley lies between two major strands of this system, as shown topographically by the faceted spurs and linear trend of the ranges. Huge blocks of basement rocks, of probably landslide origin, lie along the base of the Santa Rosa Mountains (Sharp, 1967, pl. 1).

OPTIONAL SIDE TRIP AND STOP: FONTS POINT

Excellent view southward of dissected and deformed Late Cenozoic strata of the Borrego Badlands, assigned to the Palm Spring and Borrego Formations (Crowell and Baca, Chap. 10, this volume).

STOP: SALTON SEA OVERLOOK

We are standing on a pediment surface armored with desert pavement extending southeastward from the Santa Rosa Mountains, and underlain by beds of the Pleistocene Ocotillo Conglomerate. Unconformably beneath these beds are sandstone and siltstone layers, folded and faulted, consisting of the non-marine Plio-Pleistocene Palm Spring and Borrego Formations (Crowell and Baca, Chap. 10, this volume). Note our position with respect to the rims of the Salton Trough, the pattern of sedimentation taking place around us, and the tectonics responsible for the topography.

SALTON SEA OVERLOOK TO RED HILL

Drive E along Hwy S-22 to Hwy 86 at Salton City, then SE about 8 mi to paved road into the Salton Sea Naval Base. Take this road to the proximity of a barchan dune and tufa-covered hillocks if there is time. Otherwise, proceed along Hwy 86 another 20 mi to Westmorland. Turn N in the center of the town on S-30 (Forrester Rd.), and around curves to continue N on Gentry Rd. Leave S-30 at Eddins Rd. and continue directly N on Gentry Rd. to Sinclair Rd., then E one mile to Garst, and N 1.5 mi to Foss Rd. and W to the Red Hill volcanic dome and marina. Drive up to broad saddle between the two summits, and park in flat near dump. Walk 100 m or so up hilltop on the N for views of the Salton Sea region and of the volcanic rocks.

On leaving the Salton Sea overlook, our route drops down to the floor of ancient Lake Cahuilla, a lake that occupied the Salton Trough from time to time between 1600 and 300 years ago (Hubbs and Bien, 1967; Crowell and Baca, Chap. 10, this volume). Shorelines are conspicuous as well as bottom features formed in shallow water, such as spits, bars and mantling of sediment containing abundant small fossils. The shoreline is near present sea level. The Salton Sea was formed during the interval between 1905 and 1907 when levees along the Colorado River broke and water entered the deepest part of the Salton Trough along New River, inundating the railway and other features. We cross the New River N of Westmorland.

OPTIONAL SIDE TRIP AND STOP:
BARCHAN DUNES AND TUFA-MANTLED HILLOCKS

Between one and two miles E along the paved road leading to the Salton Sea Naval Base, hillocks N of the road (with barchan sand dunes on beyond) are noticeable. Park and examine these on foot. Beds of the Plio-Pleistocene Borrego Formation and Pleistocene Brawley Formation are folded and faulted (Wagoner, 1977). Odd-shaped concretions are abundant. Resistant sandstone layers form hills that extended above the level of ancient Lake Cahuilla, and are coated with calcareous tufa. The sand dunes were studied by Long and Sharp (1964) and by Norris (1966).

We pass the Salton Sea Geothermal Field in approaching the Salton Sea from the S. To the W of our route along Gentry Rd. N of Westmorland, wells of the Magma Power Company, under development for the San Diego Gas and Electric Company, reach depths greater than 8000 ft, and about 22 mi to the SE, the Wilson No. 1 well reached 13,443 ft (Muffler and White, 1969). Samples from these wells show increasing induration with depth along with increasing metamorphism that reaches the greenschist facies. Temperatures range up to 360°C at 7100 ft, and some wells produce brines containing over 250,000 ppm dissolved solids, primarily Cl, Na, Ca, K and Fe. Corrosion problems involved in bringing the geothermal field into heat production are therefore considerable, and at present the only region now producing energy within the Salton Trough is the Cerro Prieto Field in Mexico, a few miles S of Mexicali. During 1978, however, 13 geothermal wells were drilled in the Imperial Valley and a new field (South Brawley) has just been discovered. Within it, bottom-hole temperatures of 475° to 500°F prevail at 13,381 ft, with an initial one-hour flow test at a rate of 60,000 bbl/day from deep-fracture production (Blaisdell, 1979). The first geothermal power plant will begin generating electricity at East Mesa this year, and six more are in stages of design and construction within the valley. The Imperial Valley geothermal region is inferred to lie above spreading centers at the divergent boundary between the North American and Pacific lithospheric plates.

STOP: RED HILL

Red Hill (or Red Island) consists of two of the five rhyolitic plugs or domes that intrude Quaternary sediments near the SE shoreline of the Salton Sea (Fig. 31) (Robinson, Elders and Muffler, 1976). They are composed of low-calcium, alkali rhyolite, pumice, and obsidian with from 1 to 2% crystals. Xenoliths of low-potassium tholeite basalt and partly melted granite, many showing strong hydrothermal alteration, have been analyzed by Robinson, Elders and Muffler (1976). They interpret the bimodal basalt-rhyolite assemblage as formed by partial fusion of mantle peridotite in two stages, forming successive rhyolitic and basaltic melts. Compositions and textures suggest that the granite xenoliths are fragments of basement rather than the crystallized equivalents of the rhyolitic magma. The domes are interpreted to lie above a hot-spreading center underlain at great depth primarily by a mantle diapir that has broken and fragmented the attenuated basement of older continental rocks as the Pacific and North American plates diverged.

NE of Red Hill lies an abandoned CO_2 field that produced this gas from 1934 to 1954 from 54 wells with depths ranging from 500 to 700 ft at pressures exceeding the hydrostatic. The gas was used mainly for manufacturing "dry ice." Abundant CO_2 is thought to have been released by decarbonation accompanying metamorphism of the young sediments (Muffler and White, 1969), then the CO_2 migrated upward into the field. The initial source of the carbonate was probably detrital carbonate grains eroded from older sedimentary formations of the Colorado Plateau region and brought to the Salton Trough by ancestral Colorado Rivers.

OPTIONAL SIDE TRIP:
ACTIVE FAULTING - BRAWLEY AND IMPERIAL FAULTS

From Westmorland, drive 7 mi SE on Hwy 86 to Brawley, thence E through Brawley on Hwy 78 to Hwy 86; turn S (right) on Hwy 86 and drive S 5.3 mi to Keystone Rd. Turn left (E) onto Keystone Road and drive 5 mi E past Mesquite Lake to McConnell Rd. Jog N on McConnell Rd., then E onto the continuation of Keystone Rd. The Brawley fault crosses Keystone Road about 1/4 mi E of McConnell Rd. Another en echelon strand crosses Harris Rd. 1/4 mi E of McConnell Road, 2 mi S of Keystone Rd. To reach the Imperial fault, drive 4.5 mi S on McConnell Rd. from Keystone Rd. (2.5 mi S from Harris Rd.) to Worthington Rd. Turn right (W) at Wilson's Corners onto Worthington Rd. The Imperial fault scarp has a zone of cracks in the asphalt at the base of the scarp, about 1/4 mi W of McConnell Rd.

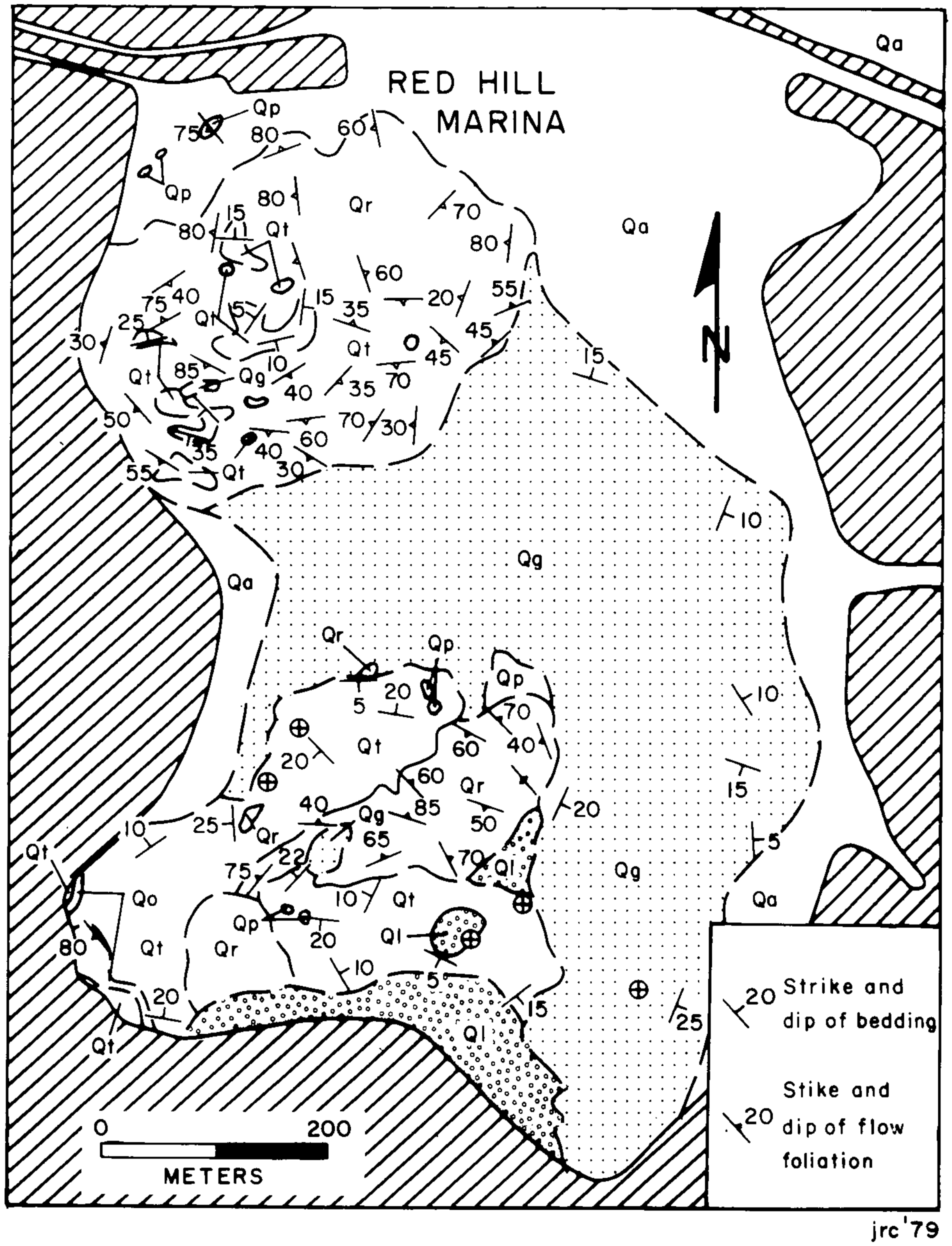

Fig. 31. Geologic map of Red Hill. Qr, rhyolite (dominantly lithoidal) that forms north and south protrusions; Qo, obsidian and flow breccia; Qt, subaqueous pyroclastic material; Qg, gravel and sand; Ql, lag gravel; Qa, alluvium. Diagonal lines indicate area covered by Salton Sea in October 1964. Redrawn from Robinson, Elders, and Muffler, 1976, Fig. 5.

At the SE corner of Hwy 86 and Keystone Rd., note that the ground surface is about 30 m below sea level as indicated by the sea level mark on the Holly Sugar silos.

Mesquite Lake is believed to be a tectonic sag centered over a small pull-apart in the floor of the Salton Trough (Keller, Chapt. 6, this volume). Seismic refraction and gravity data show that about 6 km of sediments fill the pull-apart in this part of the Salton Trough (Keller, Chap. 6, this volume).

The Brawley fault, which was discovered by earthquake studies in 1975 (Hill, Mowinkel and Peake, 1975; Sharp, 1976) is an active, N-striking fault strand in a right-stepping en echelon arrangement between the Imperial fault on the SW and the southeasternmost end of the San Andreas fault. En echelon surface cracks formed along a 10.4-km segment of the Brawley fault during the earthquake swarm of January and February 1975 (Hill, Mowinkel and Peake, 1975; Sharp, 1976; Keller, Chap. 5, this volume). Surface displacement was largely vertical over a zone 50 m wide, reaching a maximum of 0.2 m at Keystone Road. The scarp (E side relatively uplifted) can be seen in the roadway. Lines and arrays of nails across cracks in the asphalt are temporary benchmarks used by various investigators to monitor surface movements. Note that the sides of the adjacent irrigation ditches are not noticeably offset laterally, showing that the only substantial component of slip has been vertical.

The zone of en echelon cracks extended SSW from Keystone Rd. across McConnell Rd. in 1975, but another en echelon zone of cracks cuts across Harris Rd. at the base of an old, west-facing 5-m-high scarp. This scarp forms the E side of a graben centered around Mesquite Lake. The W side of the graben is a 5-m-high, NE-facing scarp along the Imperial fault. This scarp and associated cracks in the asphalt roadway can be observed on Worthington Rd. Note that the center line of the roadway is displaced about 1 m right-laterally over a zone about 10 m wide at the base of the scarp. About 1 m of vertical displacement occurred at this locality in the 1940 Imperial Valley earthquake.

OPTIONAL SIDE TRIP:
ZONE OF ACTIVE HORIZONTAL CREEP, IMPERIAL FAULT

From Wilson's Corners at the intersection of Worthington Rd. and Hwy 111, take Hwy 111 S 3.7 mi to Evan Hewes Road, turn left (E), drive E about 1.5 mi to Bowker Rd. 0.2 mi E of Bowker Rd. the railroad tracks on the N side of the highway are gently bent right-laterally over a zone about 30 m wide.

Sight E or W along the line of utility poles just S of the railroad tracks, and note that they are offset right-laterally about 1 m adjacent to the bend in the tracks. Fresh cracks are present in the pavement of Evan Hewes Rd. Observe them with care, however, because the traffic is fast and often heavy.

> Return to the field trip route by taking Hwy 111 N to Brawley, and continue N through Calipatria and Niland, thence NW along the NE edge of the Salton Sea to the optional stop at Salt Creek.

The route from Brawley to Salt Creek goes through Calipatria, site of the allegedly tallest flagpole in the United States. The top of the flagpole, when originally built, reached some 275 feet up to sea level. The route crosses the buried traces of several NW-striking en echelon faults whose presence and locations are inferred largely from earthquake data.

RED HILL TO MECCA

> Return from Red Hill E to Garst Rd., then S 1.5 mi to Sinclair Rd. and E 3.5 mi to Hwy 111 and N and NW for 47.3 mi along the NE shore of the Salton Sea to Mecca. About a mile NW of the Imperial-Riverside County line, with Bat Caves Butte on the E, the highway dips to cross Salt Creek adjacent to a railroad trestle. The Salt Creek Optional Stop is to the NE just beyond the railroad.

From Niland to Salt Creek, the route along Hwy 111 is parallel to the front of the Chocolate Mountains NE of the highway. The entire mountain area is an active bombing range which has precluded detailed studies of the geology. In general, however, the rocks comprise Mesozoic (?) Orocopia Schist overthrust by Precambrian gneiss which is intruded by Mesozoic granitoids, and all intruded by and overlain by dikes and flows, respectively, of Tertiary volcanic rocks (Sylvester and Bonkowski, Chap. 7, this volume; Korsch, Chap. 9, this volume).

OPTIONAL STOP:
SAN ANDREAS FAULT ZONE AT SALT CREEK

Nonmarine beds of Plio-Pleistocene silt, sand and clay are tightly folded and faulted adjacent to the San Andreas fault zone beneath and upstream from the railroad trestle across Salt Creek (Babcock, 1974). Structures in this vicinity fit the simple-shear scheme.

MECCA HILLS

Continue NW along Hwy 111 about 17 mi to the intersection with Hwy 195 at Mecca. Turn NE onto Hwy 195, follow it through Mecca and eastward toward the Mecca Hills. After crossing the Coachella Canal, drive NW along the gravel road that is parallel to the power lines about 3 mi from the paved road to the mouth of Painted Canyon. Vehicles can proceed a few more miles up the canyon where there are picnic tables and pit toilet facilities, but no water.

The Mecca Hills (Sylvester and Smith, 1976; Sylvester and Smith, Chap. 12, this volume) are one of three tectonic culminations along the San Andreas fault in the Salton Trough together with the Indio and Durmid Hills. The Mecca Hills are warped and uplifted between the San Andreas fault on the SW and the Painted Canyon and Hidden Spring faults on the NE. Precambrian and Mesozoic basement rocks are exposed in the core of the Mecca Hills, and the 30° NW plunge of structures offers a deep structural profile. The San Andreas fault itself strikes parallel to the course of the gravel road leading to Painted Canyon from Hwy 195, about 1/2 mi within the Mecca Hills. Its course is marked by streaks and talus-strewn slopes of dark red-brown clay-gouge. Dark brown, gravel-strewn slopes and hillocks in the foreground are underlain by Pleistocene Ocotillo Conglomerate which contains schist debris derived from the Orocopia Mountains to the E and subsequently offset 15 mi NE along the San Andreas fault. The higher, ruggedly sculptured part of the Mecca Hills is underlain by the Plio-Pleistocene Palm Spring Formation, consisting of sandstone and conglomerate with interbeds of greenish-gray siltstone. In the core of the Mecca Hills, the lower part of the Palm Spring Formation is interbedded with and underlain by the Mecca Formation, a coarse, dark reddish-brown unit of torrentially deposited breccia and conglomerate. The Mecca Formation, in turn, lies nonconformably on a heterogeneous basement terrain of Precambrian gneiss, Mesozoic granitoids and greenschist, and Tertiary hypabyssal intrusive rocks. The hills have formed since mid-Pleistocene time by folding, faulting, and broad arching and uplift.

At the mouth of Painted Canyon, turn southeast to the pit where red clay has been quarried for lining metal for irrigation canals. The road leads to the mouth of Skeleton Canyon. Park in the broad flat at the mouth of this canyon.

The main trace of the San Andreas fault strikes across the mouth of Painted Canyon to the parking place and is marked by dark red-brown gouge at the mouth of Skeleton Canyon.

STOP: SKELETON CANYON AND AIKEN'S CORNER

Examine the slickensided clay gouge in bulldozer cuts at the mouth of Skeleton Canyon. The gouge, apparently reconstituted from Plio-Pleistocene siltstone, has been deformed within the San Andreas fault zone and here is squeezed upward to the surface. Examine also the lozenge-shaped chunks of sandstone that are caught up as phacoids in the clay gouge. Walk downstream around the spur and thence SE for about 1/3 mi, climb a small saddle to look down into Aiken's Corner. This is a low pocket of tight folds, at places nearly isoclinal, with hinge lines that plunge about 70° NW. The beds involved are Plio-Pleistocene in age, and the folds themselves represent disharmonic folding in the core of an overturned asymmetric syncline beneath an overthrust flap in the footwall of the San Andreas fault. Please do not walk on the delicate beds, but on the alluvium in the rivulet channels.

Walk SW from the folds down the drainage channel for about 1/4 mi to exposures of steeply dipping gravels of the Ocotillo Formation (Pleistocene). These beds overlie the Palm Spring Formation unconformably and have been displaced by right slip from 8 to 15 mi from the nearest available sources of basement rock in the Orocopia Mountains. Note the imbrication of schist pebbles and channeling which show the transport and facing directions, respectively.

Return to Painted Canyon, turn right on the main gravel road up the canyon.

The general structure traversed by the road is as an asymmetric anticline with basement and a complex zone of faulting in its core. However, because of strike slip on that fault, the structure is much more complex. From the San Andreas fault zone at the mouth of Painted Canyon, the road up Painted Canyon crosses the Skeleton syncline which, because of a local structural depression, is not well expressed in the canyon walls except for a few gentle reversals of dip. About 1/4 mi up the canyon, however, the dip of the beds is consistently down-canyon (SW) on the SW flank of the main anticline. The generally thin-bedded, gently dipping, tawny-colored sandy and conglomeratic beds constitute the upper part of the Palm Spring Formation. About 1/2 mi up the canyon, in the vicinity of the picnic tables and pit toilets, the sandstone and conglomeratic strata have interbeds of greenish-gray siltstone. These strata, which are overturned locally, constitute the lower member of the Palm Spring Formation. All of the Palm Spring Formation in the Mecca Hills represents coalescing alluvial fan deposits, derived from mountains NE of the Mecca Hills. On the SW limb of the anticline, the Palm Spring Formation is more than 4000 ft thick, whereas it is less than a few hundred feet thick NE of the Painted Canyon fault in the core of the anticline.

Up-canyon, around the corner from the picnic facilities, the Palm Spring Formation is underlain by the dark red-brown Mecca Formation, torrentially deposited breccia and conglomerate of locally derived gneiss, schist and granitoids. The contact between the Mecca and Palm Spring Formations on the NW canyon wall is a minor fault, but not on the SE. About 1/4 mi up-canyon from the Mecca Formation are vari-colored outcrops of highly fractured basement, including black gneiss, white granitoids, and orange felsic hypabyssal intrusive rocks. The contact of the Mecca Formation with the basement is a buttress unconformity (Fig. 32) which has been folded and faulted. The Painted Canyon fault cuts through the central part of the basement outcrop on the NW side of the canyon, but on the SE side one of the main strands of the fault forms the contact between the basement and the Mecca Formation.

STOP: PAINTED CANYON FAULT

A rather rigorous hike of about 3 hours' duration and a mile in length will be taken along the Painted Canyon fault NW of Painted Canyon. We shall examine the cataclastic deformation of the basement rocks, the geometry of the Painted Canyon fault where it dips steeply in canyon bottoms to nearly flat attitudes high on ridge crests. We shall reach vantage points from which to see the contrast in deformation styles of different parts of the Mecca Hills, especially the arrangement of tight folds and high- and low-angle faults in the footwall block of the Painted Canyon fault (see Sylvester and Smith, Chap. 12, this volume).

Continue up-canyon to the broad open part of the canyon about 200 m NE of Painted Canyon fault and the basement outcrops. Nearly vertical and overturned vermillion and tawny-colored strata belong to the Mecca and Palm Spring Formations, respectively, and are on the NE limb of the simplistic anticline transected by Painted Canyon. High on the NW canyon wall, flat-lying beds which are structurally and stratigraphically continuous with beds farther up-canyon, tectonically overlie the nearly vertically dipping beds. The contact, which is somewhat obscured by talus, is one of a family of low-angle faults associated with the Painted Canyon fault (see canyon wall sketches, Sylvester and Smith, Fig. 27 Chap. 12, this volume).

STOP: UPPER PAINTED CANYON

Just beyond the rockfall are exposures of black Precambrian

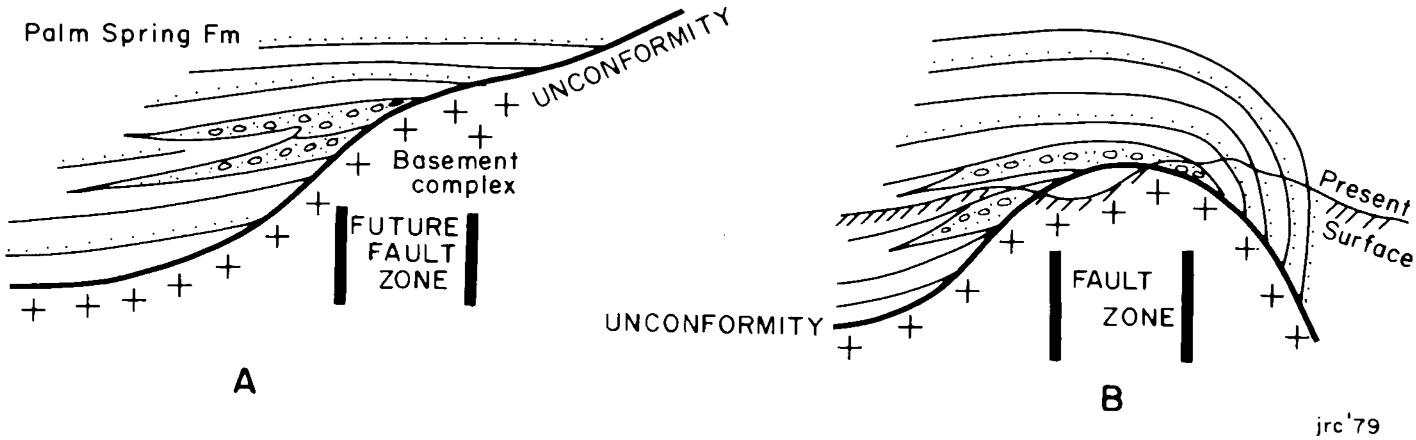

Fig. 32. Schematic diagram showing development of folded buttress unconformity along Painted Canyon fault, NW wall of Painted Canyon.

gneiss, overlain nonconformably by a thin veneer of dark reddish-brown breccia partly in channel-fillings in the basement surface. The clasts comprise locally derived fragments of gneiss and rocks which crop out a short distance up-canyon, including Orocopia Schist, anorthosite, syenite and related rocks. Walk up-canyon to observe the relatively unfractured nature of the gneissic basement and recall the shattered nature of the same rocks down-canyon at the Painted Canyon fault. The nonconformity climbs higher on the canyon walls up-canyon to the NW. About 1/2 mi from the rockfall, there is a dry waterfall in the gneiss. Scramble up the dry waterfall with care and continue up-canyon about 1/4 mi through basement outcrops of anorthosite with mafic segregations, and related rocks. These rocks were correlated with similar ones in the San Gabriel Mountains, 175 mi NW of the Mecca Hills on the other side of the San Andreas fault (Crowell and Walker, 1962) and are one of the key "tectonic tracers" used to demonstrate great strike-slip on the San Andreas fault (Crowell, 1960, 1962, 1979).

Return to vehicles, drive down Painted Canyon and back to the paved Hwy 195. Turn left and drive NE up Box Canyon noting the geological features on the way. It is about 15 mi to the intersection with Interstate 10.

In driving up Box Canyon note in turn: the nondescript crossing of the San Andreas fault zone about 1/2 mi from the intersection with the Painted Canyon turnoff; a zone of 1/3-mi-wide steep and irregularly-dipping strata between the San Andreas and Skeleton Canyon faults; a local unconformity in the Palm Spring Formation that has been folded in a gentle syncline; and numerous folds and faults along the canyon over the next few miles. The road trends generally obliquely to structure in this badlands terrain, so that structural correlation and continuity from one side of the road to the other are not readily apparent. Note the coarsening of strata up-canyon from distal to proximal parts of the alluvial fan sequence. The upper part of the canyon is underlain by relatively flat-lying beds of coarse conglomerate that lap onto dark-colored basement rocks in an irregular buttress unconformity such as that in Painted Canyon.

STOP: SHAVERS WELL

In the vicnity of Shavers Well are outcrops of the Orocopia Schist, a greenschist facies albite-chlorite-mica schist with several minor folds. This rock unit, probably ensimatic in origin, is confined to the footwall of the great Chocolate Mountain-

Orocopia-Vincent thrust system of probable latest Mesozoic age. The volcanic rocks, graywackes and mudstones that have since been metamorphosed may have been deposited in an ancient back-arc basin associated with Mesozoic subduction, or within an elongated rhomochasm 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 displaced about the Transverse Ranges region by Late Cenozoic right-slip movements.

Upon leaving Shavers Well, we drive out on alluviated Shaver Valley between the Orocopia Mountains to the SE and Little San Bernardino Mountains to the N. Structure is complex and rock types are diverse within the Orocopia Mountains. We pass close to outcrops of marine Eocene strata (Maniobra Formation) in Buried Mountain on the left (NW side of the road), but exposures here are rather poor. Within the eastern Orocopia Mountains, however, about 5000 ft of these strata are well exposed. Their likely offset counterparts are found about 180 mi to the NW on the other side of the San Andreas fault in the north-central Transverse Ranges.

MECCA HILLS TO INDIO

From the intersection of Hwy 195 with Interstate 10, drive W 24 mi to the town of Indio.

I-10 trends parallel to the Little San Bernardino Mountains on the N, parallel to the inferred trace of the Chiriaco fault, one of a number of major E-striking faults NE of the San Andreas fault in the Salton Trough region. These mountains are composed largely of Mesozoic plutons that intrude older gneisses, some of which are probably of Precambrian age. Near the divide, before descending into the Salton Trough, the alluvium is broken by several faults, related either to the Hidden Springs fault zone (a splay from the San Andreas fault in the Mecca Hills) or to the Clemens Well fault zone (a major fault subparallel to the San Andreas fault in the Orocopia Mountains). Note deformed alluvium near the San Andreas fault zone while driving down the grade. Also, with clear weather there are good views of the narrow NW end of Salton Trough, the rugged Santa Rosa Mountains to the SW, and San Gorgonio Pass (between Mt. San Jacinto with an elevation of 10,786 ft and Mt. San Gorgonio [Greyback] with an elevation of 11,502 ft).

THE INDIO HILLS

From Indio, take Dillon Rd. N and NW about 15 mi from I-10 for a scenic drive along the N side of the Indio Hills; then take Thousand Palms Canyon Rd. 4-1/2 mi S through the hills to Ramon Rd.

The Indio Hills are another tectonic culmination, or "porpoise," like the Mecca and Durmid Hills in the San Andreas fault zone. The hills are comprised of folded and faulted strata belonging to the Palm Spring and Imperial Formations; a few isolated outcrops of granitic basement rocks are exposed at the SE end of the hills, but their relation to the overlying sedimentary rocks is not clear. Two faults bound the uplifted part of the Indio Hills: the Banning fault on the SW side and the Mission Creek fault on the NE side, constituting the N and S branches of the San Andreas fault. The two faults merge together at the SE end of the Indio Hills where they continue SE as the San Andreas fault. The San Andreas fault crosses Dillon Rd. 0.6 mi N of I-10 and is marked by a prominent growth of vegetation due to impounding of southward-flowing groundwater. Within the saddle between the Indio and Mecca Hills, a tectonic depression, the San Andreas fault is marked by south-facing scarps in the alluvium and vegetation contrasts reflecting other groundwater barriers beneath the surface.

Groundwater barriers are especially prominent in the Indio Hills; they are marked by lush growth of vegetation, especially palm trees (the moisture-loving native California fan palm [Washingtonia filifera] is a "trademark" of these oases). Thousand Palms, about a mile S of the intersection of Thousand Palms Canyon Rd. and Dillon Rd., is one such oasis along the NE-facing scarp of the Mission Creek fault. The water table surface slopes S from the Little San Bernardino Mountains, and pulverized rock along the fault trace dams subsurface water to the extent that the ground on the NE side of the fault is moistened; locally there are active surface springs. Thousand Palms Canyon Rd. crosses the trace of the Banning fault at Willis Palms about 1-1/2 mi down-canyon from the Mission Creek fault. The fault is marked by a straight and prominent SW-facing scarp with abundant palm trees at its base. The structure of the Indio Hills along Thousand Palms Canyon Rd. between the two faults is a gentle syncline in alluvial fan deposits of the Late Pleistocene Ocotillo Formation. Light-colored outcrops W of Willis Palms are nearly vertical strata of the Imperial Formation. Exposures are also present in the NW part of the Indio Hills, but it is not known to crop out NE of the Mission Creek fault.

At the intersection of Thousand Palms Canyon Rd., turn left (E) onto Ramon Rd., follow it around a right curve where it turns into Washington St. Continue S on Washington St. to the freeway frontage road (Varner Rd.). Turn left (E) onto Varner Rd.; proceed one mile to Adams St. Turn left (N) onto Adams St.; follow it one mile to Ave. 38 and turn right (E). Proceed 2 mi to Madison St.; turn left (N) on dirt road and drive NW along base of a dike for a short distance.

OPTIONAL STOP: FAULT GEOMORPHOLOGY ALONG THE BANNING FAULT AT BISKRA PALMS

Geomorphic features related to, and characteristic of, faulting are well exposed along the SE part of the Banning fault in the Indio Hills. Offset and beheaded alluvial fans and stream courses, pressure ridges, sags, and fault scarps have been mapped and studied by E. A. Keller and his associates and are described in another field guidebook (Norris, Keller and Meyer, 1979). Of particular significance at this stop is a beheaded alluvial fan offset NW several hundred meters right-laterally from the canyon feeding the present fan. Individual stream courses on the surface of the fan are also beheaded, and the spacing between the drainages lead to the inference that offsets along the fault take place in jumps of from 4 to 7 m at a time.

INDIO HILLS TO WHITEWATER CANYON

Retrace route back to Washington St., thence back to I-10. Take I-10 westbound 22 mi to the turnoff to Whitewater Canyon. Go right (N) up Whitewater Canyon 5 mi where road ends at a trout farm.

Garnet Hill, about 17 mi on I-10 from the Washington St. onramp and on the left (S) side of the highway, is domed up along the N side of the Garnet Hill fault. A cap of coarse fanglomerate, including breccia, derived from the San Jacinto Mountains to the S, overlies the Imperial Formation. San Gorgonio Pass is straight ahead to the west with the San Bernardino Mountains on the right (N) and the San Jacinto Mountains on the left (S). Four miles farther W along I-10 brings us adjacent to an anticline in Pleistocene Cabazon Fanglomerate N of the road.

In Whitewater Canyon the Banning fault strikes N85°W across the canyon, placing Cabazon Fanglomerate on the S against granitic and gneissic rocks on the N (Fig. 33). A prominent vegetation line

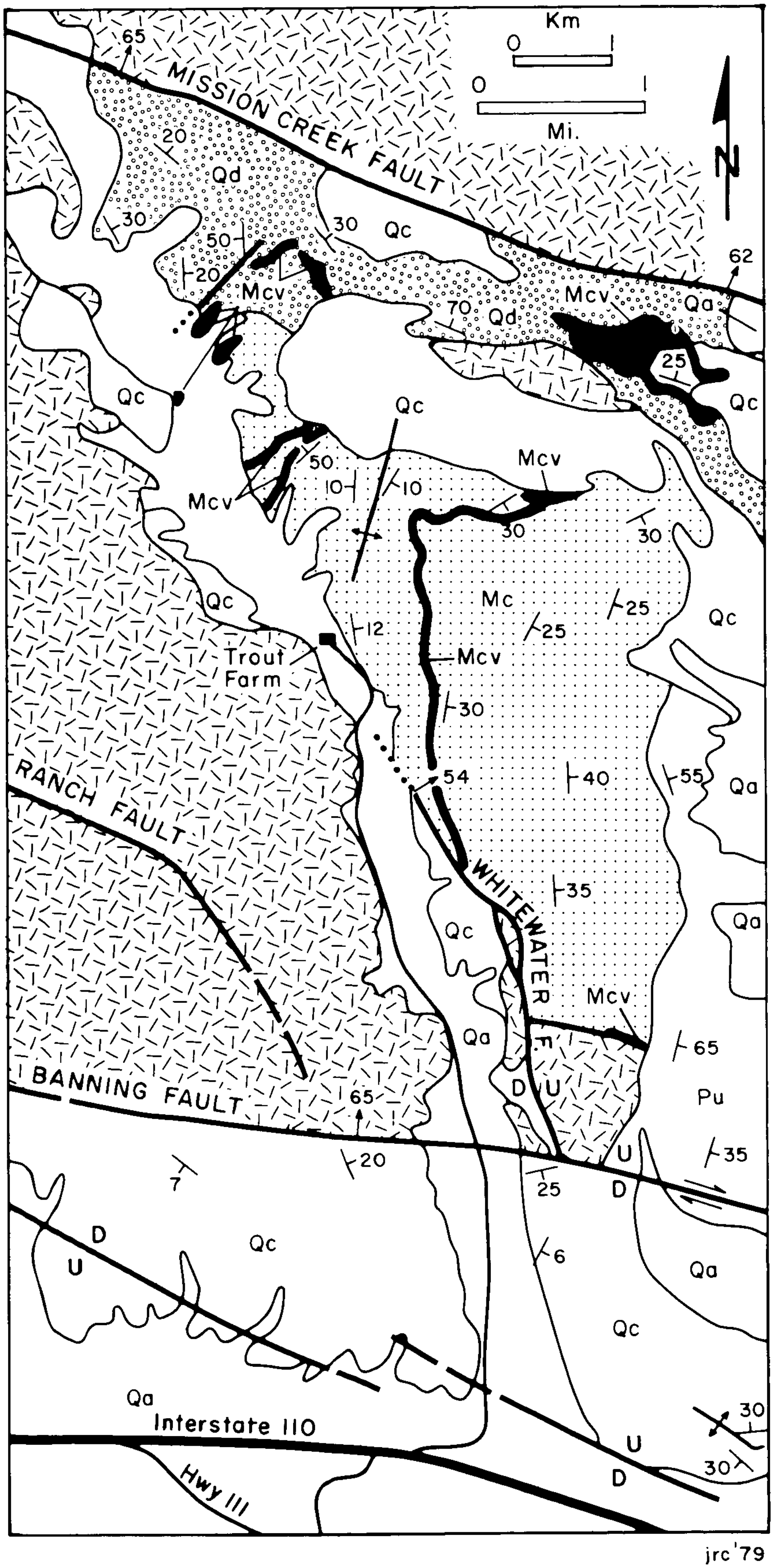

Fig. 33. Geologic map of Whitewater Canyon. Hackled pattern, gneiss. Mc, Coachella Fanglomerate; Mcv, volcanic rocks intercalated with Coachella Fanglomerate; Pu, Imperial Formation; Qd, gravels of Whitewater River; Qc, terrace; Qa, alluvium. Redrawn from Allen (1957) and Peterson (1975).

in the canyon bottom marks the trace of the fault. On the E side of the canyon the Whitewater fault (striking N30°W) juxtaposes old alluvium against Late Miocene Coachella Fanglomerate.

At the Rainbow Rancho Trout Farm, the Coachella Fanglomerate forms the abrupt east wall of the canyon. The Mission Creek fault is about 3 mi farther N up-canyon (Fig. 33). The Coachella Fanglomerate lies unconformably on basement between the Banning and Mission Creek faults. It consists of up to 1500 m of coarse conglomerate and breccia with interbedded minor sandstone lenses. Interbedded andesite flows near the base of the formation have a K-Ar age of 10 m.y. (Peterson, 1975). Peterson (1975) divided the formation into two stratigraphic units: a light gray upper unit that is predominantly fluvial and a lower, dark-colored unit that is mainly composed a debris-flow deposits. He recognized metamorphic, granitic and volcanic rocks in the fanglomerate. Paleocurrent indicators, thickness changes and downflow diminution of stone size show transport was largely NE to SW from a source across the Mission Creek fault. Particularly distinctive clasts include a slightly metamorphosed potassium-feldspar porphyritic quartz monzonite with large K-feldspar megacrysts, the so-called "Peterson porphyry," and magnetite. A possible source area with rocks matching the distinctive quartz monzonite and magnetite clasts has been recognized near the Cargo Muchacho Mountains near the International Boundary, a suggested correlation which requires 215 km of right slip (Peterson, 1975).

WHITEWATER CANYON TO PALM SPRINGS

Follow the road from Whitewater Canyon S across I-10 2 mi to Hwy 111. Turn left (E) onto Hwy 111 and follow it to Palm Springs. The Palm Springs Aerial Tramway is prominently marked by a big sign on the right (W) side of the road on the N edge of town.

The southward-flowing Whitewater River debouches in San Gorgonio Pass, forming a constricted alluvial fan that has built out southward into the Salton Trough. Huge boulders and coarse detritus attest to the flooding and erosive power of this river which drains the highest part of the San Bernardino Mountains. Powerful winds blow frequently through San Gorgonio Pass and down into Salton Trough. As they blow over the Whitewater River fan, they pick up the fine material on the fan and carry it SW, principally along I-10, causing intense sand and dust storms that have sandblasted the paint on many a car and frosted innumerable windshields.

An extensive field of low sand dunes covers the area between I-10 and Hwy 111 almost all the way to Thousand Palms, and heavy stands of tamarisk trees line the railroad to prevent sand from burying the tracks.

Allen (1957) and Proctor (1968) postulated that San Gorgonio Pass is a graben bounded by reverse faults. To be sure, the Banning fault on the N side of the pass is a high-angle reverse fault locally, but the postulated "South Pass" fault has no geophysical or geomorphic expression and, if present, is certainly deeply buried by the Whitewater River alluvial fan.

Roadcuts along the SW side of Hwy 111 expose moderately metamorphosed marble and schist whose protoliths are probably Late Paleozoic in age (Sylvester and Bonkowski, Chap. 7, this volume) and which are intruded by granitoid dikes of the Southern California batholith (Sydnor, Chap. 8, this volume).

The abrupt escarpment behind (W) Palm Springs is one of the greatest declivities in the U.S., rising from near sea level more than 10,000 ft (3000 m) over a horizontal distance of 6 km to the top of Mt. San Jacinto. Dutcher and Bader (1963) maintain that the escarpment is controlled by a N-striking high-angle fault. Thermal artesian springs, which have given the town its name and reason for being, are found along the base of the escarpment, and steep alluvial fans in Chino and nearby canyons indicate that uplift is still very active.

Fortunately, a paved road goes up Chino Canyon fan to the Palm Springs Aerial Tramway, which we shall use to help us to a point near the top of the declivity. This vantage point provides a magnificent overlook of the Coachella Valley and surrounding mountains. The superb rock exposures along the tramway are described and discussed by Sydnor (Chap. 8, this volume).

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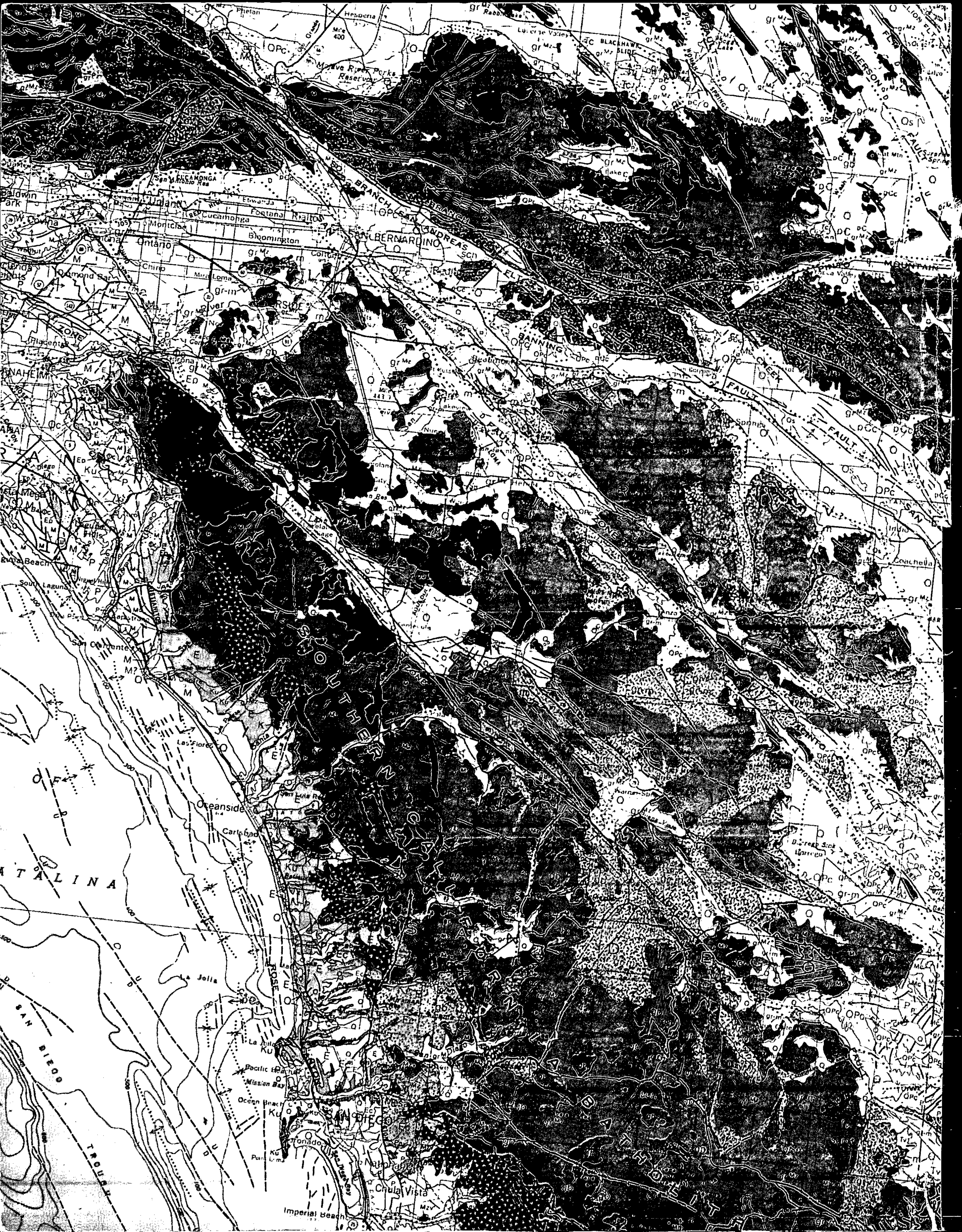

Phelan
Hesperia
Lucerne Valley
BLACKHAWK SLIDE
Mojave River Forks Reservoir
CUCAMONGA
Baldwin Park
Upland
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Cucamonga
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SAN BERNARDINO
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