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CROWELL: Late Cenozoic Basins of
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# LATE CENOZOIC BASINS OF ONSHORE SOUTHERN CALIFORNIA: COMPLEXITY IS THE HALLMARK OF THEIR TECTONIC HISTORY

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## ABSTRACT

By Early Miocene time, about 22 my B.P., the San Andreas transform belt had widened so that the margin of the continental North American lithospheric plate was fragmented and stretched. Deep and irregular basins ensued in onshore southern California, such as the Los Angeles, Ventura, and southern San Joaquin. Tectonic blocks between the basins, caught in the simple-shear system of the transform belt, were deformed and rotated, and some were squeezed upward, while others were stretched and sagged. During Middle Miocene time, deformation continued hand in hand with deposition of sediments displaying sharp facies changes that ranged from coarse continental deposits to deep-water turbidites. Eustatic flooding across irregular topography, associated with circum-Pacific plate adjustments and oceanic climate changes, resulted in the laying down of diatomaceous strata of the Monterey Formation.

By Late Miocene time, strands of the San Andreas system were well established through the region of the onshore basins. Older rocks were being displaced laterally and crustal blocks rotated as sediments accumulated. Basins changed size and shape during these tectonic events, and at least two show additional strong deepening in Early Pliocene time, corresponding with the opening of the Gulf of California. Crustal mobility of the region during the late Cenozoic, and continuing vigorously today, is now proven, but details of the tectonic history are only now being elucidated. Data are needed from paleomagnetism, paleobathymetry, facies analysis, diagenesis, paleothermometry, paleobarometry, and deep geophysical probing, in fact, from all subdisciplines of the geological sciences.

The Salton Trough and the Gulf of California provide an example of deformation and deposition occurring today in an active continental rift or divergent plate boundary associated with oblique transform displacements. Similar processes are deemed to have acted in forming late Cenozoic basins of southern California, but the products of these processes are now deeply buried and attenuated, and affected by overprinted tectonic and thermal events. The rocks in the regions of these basins are usefully regarded as pre-basinal and pre-rift, and the strata deposited within basins (basinal) as syn-rift and post-rift sequences. A large proportion of the thick sedimentary sequences contained within the basins (both basinal and post-rift), and lapping well up across their margins, is the result of late cooling of the lithosphere attended by thermal contraction and subsidence.

## INTRODUCTION

Beginning in Early Miocene time, the continental crust of southern California has undergone several episodes of stretching, fragmentation, and rotation leading to the development of sedimentary basins. These basins are part of the wide and splintered transform plate boundary where the Pacific lithospsheric plate meets the North American plate. Some basins lying onshore are here described briefly, but with an emphasis more on concepts and approaches today receiving attention from the research community than on their history, which is still only partly known.

The recognition of great lateral mobility of crustal blocks is adding a perplexing element to our perceptions of basin histories. New studies involving paleomagnetism, thermal history, paleobathymetry, diagenesis, and deep seismic investigations require melding as we attempt to reconstruct the tectonic evolution of the basins through geologic time. Paleomagnetic data show rotation of tectonic domains, but it is still unclear how these fit into a regional kinematic synthesis (Luyendyk *et al.,* 1980). The technique of "backstripping" is only beginning to be applied (Steckler and Watts, 1982; Dickinson *et al.,* this volume). In this procedure, the sedimentation and subsidence history in a logged well is worked out by "unpeeling" the effects of compaction, diagenesis, and fluid changes with depth. Paleotemperature and paleobarometric interpretations from studies such as those involving clay-mineral paragenesis and vitrinite reflectance (e.g., Scholle and Schluger, 1979) are only very briefly mentioned in the California published literature. Our understanding of basin evolution is, therefore, incomplete. Here, I review some of the inferences concerning California basins, and reflect on what we need to learn. Perhaps, we can glean ideas of use in understanding California onshore basins, as well as others, such as those offshore.

Brief comments here focus on several basins, such as the Salton Trough and Gulf of California, and the Los Angeles, Ventura, and San Joaquin basins, with only a glance at others (Fig. 9-1). They are late Cenozoic in age and are no older than about 24 my, and have undergone several stages in their development. The record for most of the southern California onshore basins is unusually complete because datable upper Cenozoic strata are widespread and facies of sediments are closely related to tectonic events. The Quaternary and Pliocene record is especially complete for some, such as in and around the Salton Trough, because basin-forming processes are now active and geomorphic data can supplement stratigraphic information in putting the tectonic history together. It is, therefore, discussed first. Stages in the evolution of younger basins, such as the Salton Trough and some in the Gulf of California, may be similar to early stages for older ones, such as the Los Angeles basin. For the older, however, the record of the early episodes may be deeply buried. Understanding of steps in their development may, therefore, come from comparing these older basins with actively evolving ones. A purpose of this paper is to speculate on the nature of the tectonothermal processes. We now know that California has been remarkably mobile during late Cenozoic times. What does this mean in regard to basin evolution?

## TECTONIC SETTING OF ONSHORE LATE CENOZOIC BASINS

Southern California has long been at or near the tectonically active margin of western North America. Pre-Miocene rocks underfoot are, therefore, complex, and these constitute the terrane overprinted by the late Cenozoic events dealt with here. This older and pre-existing terrane relects origins associated with all styles of plate boundaries: convergent, divergent and transform. Crystalline basement rocks range



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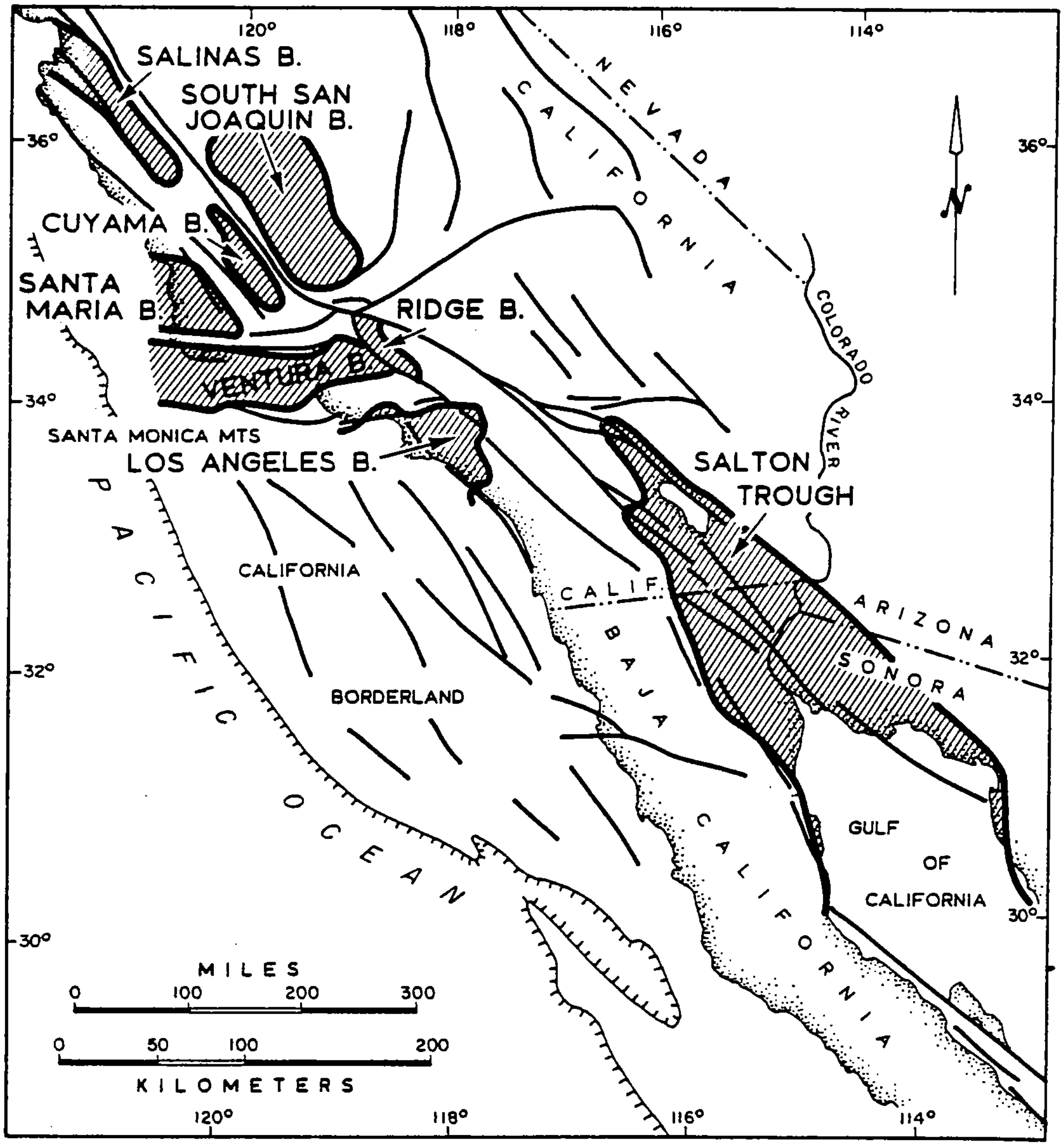


Fig. 9-1. Sketch map showing location of late Cenozoic basins in onshore southern California and Mexico. Base from King (1969).

in age from Proterozoic to middle Tertiary, and consist of both igneous and metamorphic complexes.

Huge thrust faults, such as the late Mesozoic–early Tertiary Vincent thrust system (Ehlig, 1982), have brought Precambrian and younger rocks above Mesozoic greenschists and are now enfolded within the basement. Much of coastal southern California is allochthonous above this folded and fragmented thrust system. Overlying sedimentary strata range from Upper Jurassic through



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Paleogene, and locally are incorporated within basement slabs and slices as the result of faulting and folding. These heterogeneous rocks of diverse origins were assembled through time to constitute southern California early in the Miocene Epoch, when they were overprinted in the continental region under discussion here by displacements associated with the San Andreas transform system (Atwater, 1970; Crowell, 1979; Ernst, 1981). It is with these later displacements that we are concerned here, although geologists reconstruct the arrangement of older terranes by using plate-tectonic concepts. For example, the organized Mesozoic arc and forearc arrangement has been disassembled by later tectonic events and its conceptual restoration gives clues to the mobility of crustal blocks.

The plate-tectonic setting of southern California is shown diagrammatically in Fig. 9-2. In this figure, Atwater depicts the types of plate boundary affecting southern California through geologic time beginning 30 my B.P. (the vertical coordinate), and arranged with reference to the present coastal geography (the horizontal coordinate). The reconstruction is based on the analysis and interpretation of sea-floor magnetic anomalies, and as yet, there are no satisfactory anomalies older than 5 my formed at the boundary between the Pacific plate and the North American plate (Atwater, 1970, in preparation, also, personal communication, 1985; Atwater and Molnar, 1973; Jurdy, 1984). Reconstructions are made via a circuit around the globe across the Pacific, Antarctic, Indian, and Atlantic Ocean regions. Slightly different reconstructions have resulted recently from using the assumption that deep mantle hot spots can be recognized within overlying lithospheric plates, and that these hot spots have been fixed in position through the time interval of concern (Engebretson *et al.*, 1984a; Page and Engebretson, 1984). The uncertainties in these reconstructions are also large.

In Fig. 9-2, five plots or lines show the timing of the onset of interaction between the Pacific plate and the North American plate at 29 my B.P. (the bottom of the diagram). This is the time when the East Pacific Rise arrived at the North American plate, and the Farallon plate no longer lay between the two plates along the zone of plate contact, Line 3 is the preferred time-position plot of plate touching based on plate-tectonic reconstructions, and lines 1, 2, 4, and 5 are other possibilities within the limits of confidence. The Pacific plate arrived at the North American plate 29 my B.P., but as shown on the plot, its position of incidence ranges from the vicinity of the Ventura basin (VB) on the north to near Punta Eugenia on the south when the peninsula of Baja Californian is retrofitted so that the Gulf of California is closed.

In fact, through interpretation of the geologic record, we can expect to constrain these plate-tectonic models and improve our understanding of the changing tectonic styles and effects at different times and places along the California margin. In considering the time and place of origin of the onshore basins, we must "unslide" the strike-slip faults of the San Andreas and related systems and close the Gulf of California (shown approximately as the restored coastline). In the upper or map part of Fig. 9-2, the San Joaquin (SJB), Ventura (VB), and Los Angeles (LAB) basins are shown both in their present positions, and about where they probably were at the time of their origin. The San Joaquin basin lies to the east of the San Andreas fault, and it is estimated that it has only been displaced



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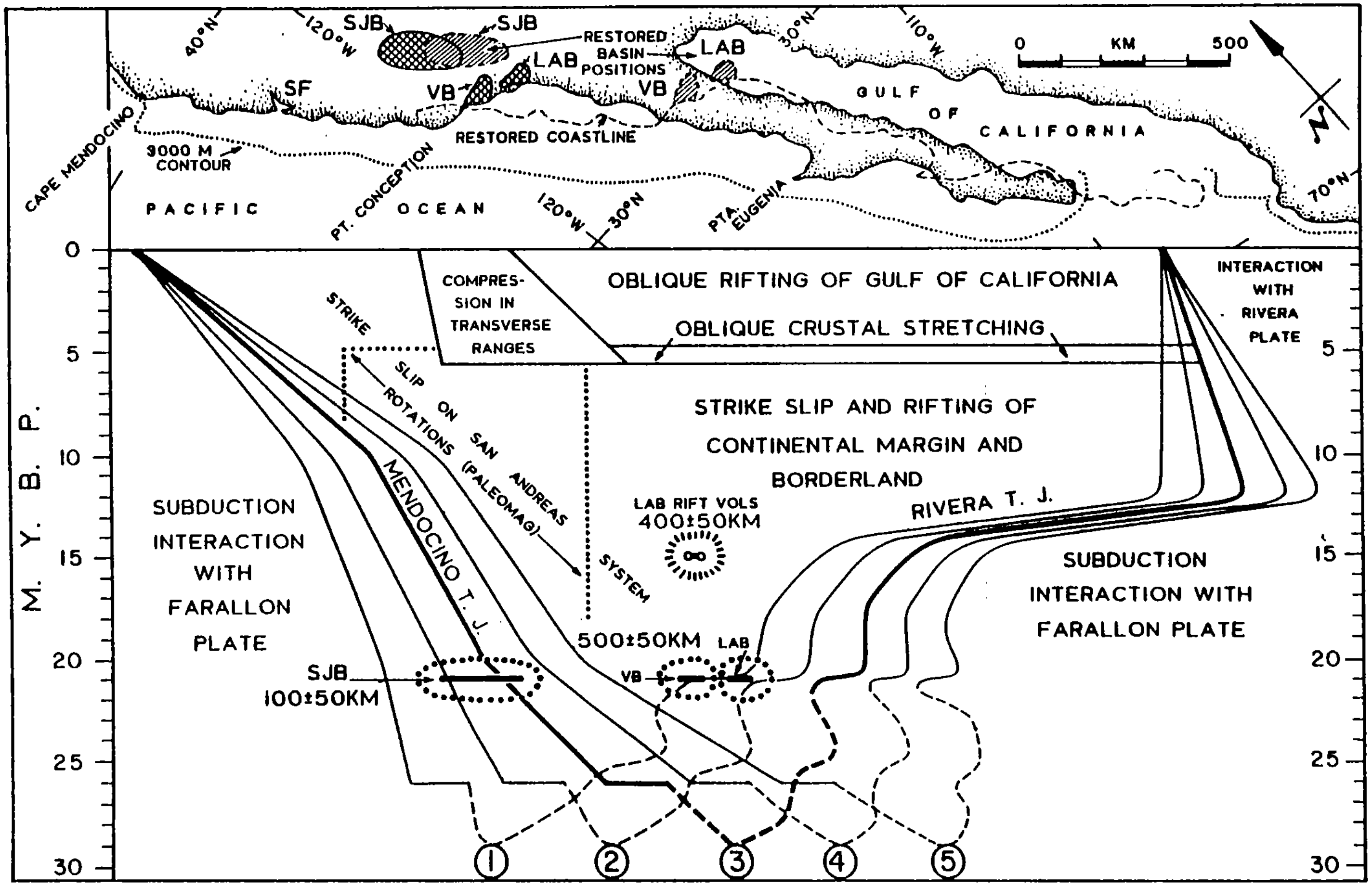


Fig. 9-2. Diagram showing plate-boundary regimes in late Cenozoic time with respect to the California and Mexican coast restored to its approximate position about 10 my B.P., based on plate-tectonic reconstruction (Atwater, 1970; personal communication, 1985). The present shoreline is shown for approximate geographic reference only. The coordinates for the diagram are geography horizontally and time vertically. Refer to text for explanation. SF, San Francisco; LAB, Los Angeles basin; VB, Ventura basin; SJB, San Joaquin basin; T.J., Triple junction.

northwestward about 100 km by right slip on faults lying farther to the east, mainly within the Basin-Range region. The Ventura and Los Angeles basins, on the other hand, lie to the west of the San Andreas fault and have been displaced approximately 400 km additionally. This includes about 320 km on the San Andreas fault and about 80 km on other faults such as the San Jacinto and Elsinore (Crowell, 1979). This estimate of 500 km of right slip for displacement relatively northwestward of the Ventura and Los Angeles basins since their origin is quite tentative and will be improved as more data come are analyzed.

Subduction prevailed along the boundary of North America in early Tertiary time (lower part of Fig. 9-2). This subduction had carried lithospheric plates lying to the east of the East Pacific Rise beneath the North American plate, and the rise itself began to affect continental rocks constituting what is now onshore California some time after the encounter of the Pacific plate with the North American plate, after 29 my B.P. This encounter was followed by tectonic stretching and basin-floor subsidence that started in the Los Angeles, Ventura, and San Joaquin basin regions about 22 my B.P., as discussed where the basins are described in the text below. The sizes and shapes of the dotted elipses at about 22 my B.P. give an estimate of confidence limits for both time and position of origin of the San Joaquin, Ventura, and Los Angeles basins with respect to the restored coast. A lapse of at least 7 my seems required for plate readjustments to reach inland to the regions of the onshore basins from the margin before they originate. An additional 7 my, or until about 15 my B.P., apparently is needed before rifting, with volcanics, affects the Los Angeles basin.

If Figure 9-2 is drawn correctly, plots 1 and 2 are more nearly correct than 3, 4, and 5. This, in turn, suggests that the Pacific plate first impinged upon the North American plate in the vicinity of northern Baja California, about halfway between the international border and Punta Eugenia (before the Gulf of California had opened). The plots also suggest that the southern end of the zone of plate interaction near the Rivera triple junction remained in the vicinity for some time, and perhaps, played a rôle in fragmenting the North American plate. Similar events at the northern end of the belt of interaction, near the Mendocino triple junction, correspondingly were involved in the origin of the Cenozoic San Joaquin basin. Data in hand at present from paleomagnetic investigations indicate tentatively that most of the rotations were completed by about 5 my B.P., and that the region affected is as shown on Fig. 9-2, within the dotted line (Hornafius *et al.,* 1986).

In short, since 29 my B.P., three factors largely controlled the sites and styles of sedimentation in onshore southern California: (1) Neogene plate rearrangements; (2) the time of arrival of the East Pacific Rise and azimuth of relative motion of the Pacific plate as it met and perhaps moved beneath the boundary belt of the Pacific and North American plates; and (3) the worldwide sea-level changes (discussed briefly below and see May and Warme, this volume). As we learn more about the time of origin of the different basins from the study of sedimentary facies, their fossils and associated volcanic rocks, we can expect to work out a chronology of when the different basins formed (Fig. 9-3). Bathymetric interpretations based on the ecology of benthic fossils suggest that these tectonic events corresponded with sharp deepening after shallow-water deposition. For

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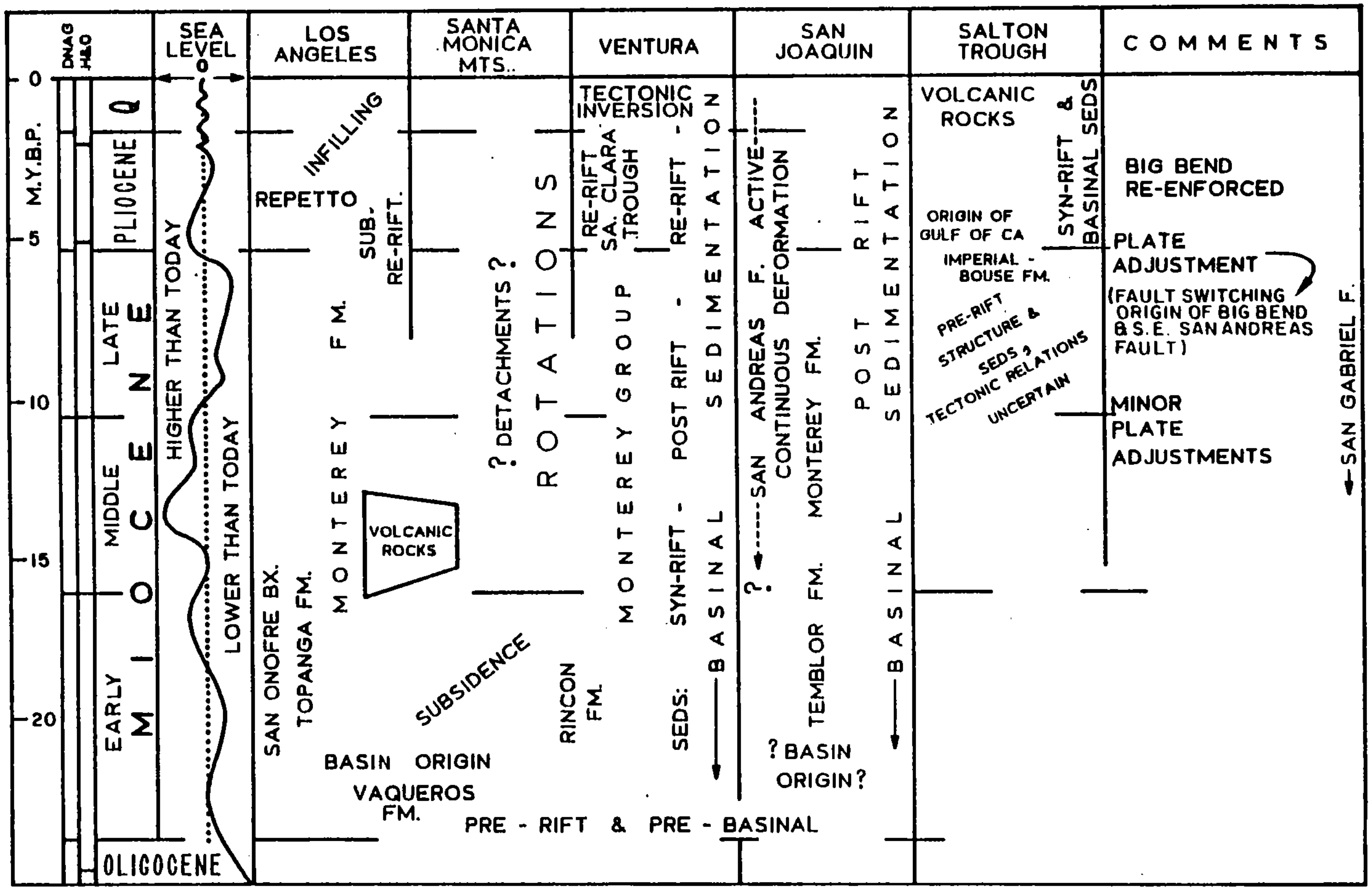


Fig. 9-3. Table showing major geological events during late Cenozoic time for some onshore basins in southern California. Two time scales are on the left: DNAG, Decade of North American Geology time scale (Geological Society of America) (Palmer, 1983); H & O, Harland et al. (1982).

example, this happened about 22 my B.P., near the beginning of the Miocene Epoch, when the shallow-water deposition of the Vaqueros Formation gave way to deep-water deposition of the Rincon Formation (Finger, 1983; also, see Dickinson *et al.*, this volume; Mayer, this volume). The marine-transgressive facies of the Vaqueros Formation closely followed widespread deposition of nonmarine beds of the Sespe and related formations during Oligocene time (Nilsen, 1984a). The relative uplift of southern California during Oligocene time is inferred to be related both to eustatic changes in sea level and to the local passage beneath the continental margin of the Mendocino fracture zone, reconstructed as extending eastward to separate two parts of the Farallon plate (Glazner and Loomis, 1984).

Geologists have only begun to look at the geologic record of California with plate-tectonic concepts and the growing knowledge of eustatic sea-level changes in mind (Hardenbol *et al.*, 1982). The documentation of the more detailed tectonic history of the region must now come through scrutiny and interpretation of the total geologic history coupled to our growing understanding of the behavior of mobile belts at the joins between lithospheric plates over the earth as a whole. Vistas are now opening on ways to acquire more data on the configuration of the lithosphere through deep geophysical probing, on the behavior and significance of thermal and diagenetic processes, improvements in dating methods, and through improved methods to interpret the bathymetry and configuration of past geographies by means of the study of sedimentary facies. Paleomagnetic investigations, as yet covering not nearly enough terranes with enough density of data, are showing that tectonic blocks in southern California are moving horizontally and rotating as they do so (Kamerling and Luyendyk, 1979; Luyendyk *et al.*, 1980; Luyendyk and Hornafius, this volume). Data and concepts applicable to southern California are coming in so quickly that geologists cannot yet write a meaningful tectonic history of the region covering the last 30 million years or so.

## SALTON TROUGH AND GULF OF CALIFORNIA

At present, southeastern California is being ripped asunder where the divergent lithospheric plate boundary within the Gulf of California extends northwestward into the North American plate and meets the San Andreas transform boundary (Fig. 9-4). The onland head of the Gulf (the Salton Trough) narrows to form the deep Coachella Valley between high mountain ranges on either side. The Salton Sea, with a surface now about 70 m below sea level, lies within the depression that is separated from the Gulf of California by a broad apron of sediment deposited by the Colorado River. Steep fault scarps on both sides of the Salton Trough divide the mountains from alluvial fans and playa flats. The topography shows that the region is active tectonically, and this is confirmed by geological and geophysical data (Elders *et al.*, 1972; Crowell and Sylvester, 1979; Crowell, 1981a,b; Johnson *et al.*, 1983). The Salton Trough is widening obliquely now, and the main pulse of rifting has gone on for only about 5 my, since the Gulf of California began opening at its southeastern mouth (Larson *et al.*, 1968; Moore and Buffington, 1968; Curray and Moore, 1984). The Salton Trough originated at

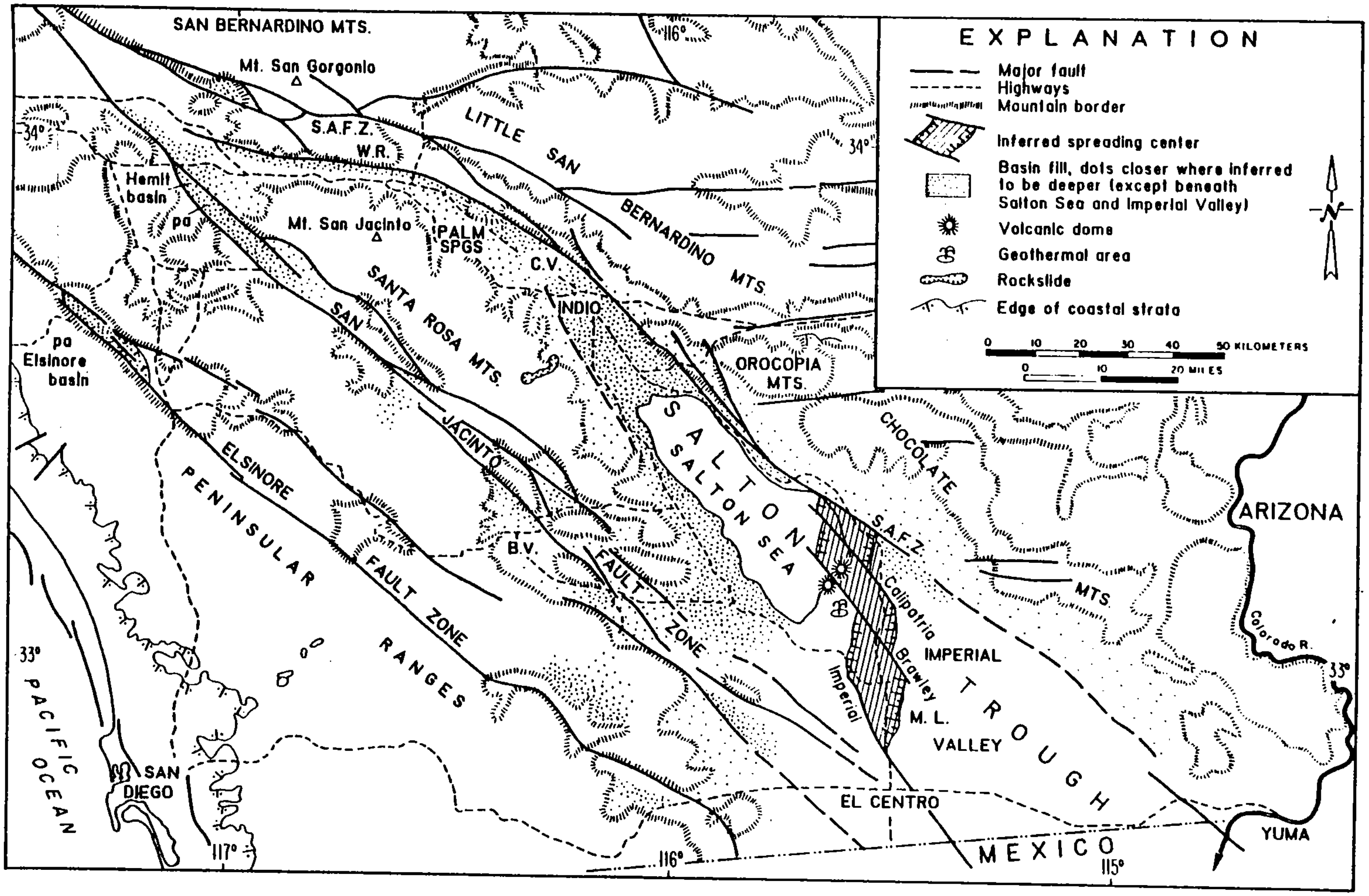


Fig. 9-4. Tectonic sketch map of the Salton Trough region. S.A.F.Z., San Andreas fault zone; B.V., Borrego Valley; C.V., Coachella Valley; M.L., Mesquite Lake; pa, pull-apart basin; W.R., Whitewater River area. Modified from Crowell and Sylvester (1979, Fig. 1).

about the same time, inasmuch as the coarse sedmentary breccias shed inward from the bordering fault scarps are of Pliocene age. They immediately overlie the marine Imperial-Bouse Formation (Metzger, 1968), which has been assigned a lastest Miocene-Early Pliocene age on the basis of foraminifera (Ingle, 1973), and K-Ar isotopic age of 3.02 ± 1.15 my from an interbedded tuff (Damon, 1967, *in* Metzger, 1968). The Gulf of California–Salton Trough region provides us with examples of the ways crustal rocks are rifted tectonically, and later infilled with sediments. Perhaps older basins in onshore California went through similar stages in their evolution when the principal belt of fragmentation lay to the northwest and before the East Pacific Rise had moved southeastward to occupy the Gulf of California and the Salton Trough.

Tectonic activity in the Salton Trough region at present is documented by recurring earthquakes and geodetic measurements, as well as by the rugged landscape and sedimentation pattern (Van de Kamp, 1973; Crowell and Sylvester, 1979; Keller *et al.*, 1982a). Several earthquakes have taken place in the region in recent years, and two have been investigated and described in detail: the Borrego Mountain earthquake of 9 April 1968 (Sharp *et al.*, 1972) and the Imperial Valley earthquake of 15 October 1979 (Johnson *et al.*, 1982). Studies of earthquake first motions, sense of slip observed at ground ruptures, and geodetic surveying show that the Salton Trough is obliquely widening in a northwesterly direction. This widening is accompanied by sagging over pull-apart depressions in the Imperial Valley region, as beneath Mesquite Lake. Gravity measurements lead to the inference that high-density rocks lie at relatively shallow depths beneath the trough. These rocks are interpreted to consist of upper-mantle and lower-crustal material that has welled up as the region has stretched. Faults and deformation patterns outline pull-apart sub-basins (Fig. 9-4) adjacent to the Salton Sea. They provide examples of incipient sub-basins nested within the broad valley, and are similar in shape to those still largely empty of sediment located within the Gulf of California far to the southeast (Lonsdale and Lawver, 1980; Lonsdale, 1985). In fact, the oblique orientation of these small sub-basins to the trends of the major transform faults and the plate boundary suggests that their direction of stretching corresponds to the direction of extension in the simple-shear system (Crowell, 1985).

The Salton Trough region has high heat flow (Lachenbruch *et al.*, 1985). This, along with the occurrence of Quaternary volcanism within the trough and high values of Bouguer gravity, suggests that the region lies above a system of hot mantle diapirs, interpreted as associated with the sea-floor-spreading mechanisms within the opening gulf (Elders *et al.*, 1972; Robinson *et al.*, 1976). Thermal expansion of the lithosphere beneath a region wider than the Salton Trough itself accounts for the uplift of the mountainous margins. The region has reached a stage in its tectonic history involving uplift and arching above an en-echelon chain of hot mantle domes. Oblique stretching of the region follows the strike of transform faults and is in accord with the inexorable gliding of the Pacific and North American lithospheric plates.

The sequence of discrete geological events discernible in the Salton Trough region includes those recorded both in basement rocks and in overlying sedimentary and volcanic rocks. In deciphering the late Cenozoic record, previous tectonic events must be disentangled from younger ones. Proterozoic, Paleozoic, and Mesozoic rocks on both sides of the trough have been highly deformed both before and after the emplacement of granitic plutons of Cretaceous and early Tertiary ages (Haxel and Dillon, 1978; Crowell, 1981a; Powell, 1982; Engel and Schultejann, 1984). Low-angle thrusting of Mesozoic and early Tertiary age has affected these rocks, and these thrust faults have, in turn, been folded and disrupted by later tectonic events. Right-slip of about 320 km has taken place on the San Andreas fault and some of its major strands during the past 12 my, so that the basement terrane of the Orocopia Mountains has its counterpart far to the northwest (Crowell, 1960, 1962, 1981a, 1982; Powell, 1982).

During the development of late Cenozoic basins, older structures within basement rocks are, at places, reactivated and involved in stretching and rotation as the basins opened. In the absence of ways to date events in the pre-basin rocks, however, it is impossible locally to determine when the overprinting took place, and accordingly, under what tectonic regime. For example, large antiforms and synforms are mappable adjacent to the Salton Trough, where schistose foliation and gneissic banding of Mesozoic and early Tertiary age have been folded. It is not known, however, whether this folding took place during Miocene deformation in association with the origin of core complexes and detachment faults, or during later simple-shear in association with late Cenozoic strike-slip faulting. In fact, in the Borrego Valley region, the trend of anticlines in Recent alluvium, at places, parallels the trends of antiforms in nearby basement terranes, suggesting that folding in both is proceeding now. Whether both structures owe their similar orientation to deformation going on today within the simple-shear regime, or whether older orientations are being rejuvenated, is uncertain. Pre-rift rocks of southeastern California reveal a long sequence of tectonic events, each overprinting the one before. These include several episodes of thrusting in pre-early Tertiary time (Crowell, 1981a) and mid-Tertiary detachment faulting and extension (Frost and Martin, 1982).

Strata deposited within the Salton Trough provide clues to tectonic events, but areas where a fairly complete stratal record is preserved and mappable are unfortunately limited in size. Moreover, much of the record of early events is now deeply buried in the middle regions of the trough, and accessible only through remote sensing. At places around the margin, however, sedimentary facies are exposed, similar to alluvial fans extending basinward today and grading distally into playa deposits. This style of tectonically controlled sedimentation has prevailed back in time for about 5 my (Crowell and Baca, 1979; Johnson *et al.*, 1983). During this interval, the Palm Spring Formation and related lateral equivalents were laid down. Inasmuch as deformation has gone on more or less continuously during this span of time, these beds were locally deformed, uplifted and eroded deeply, so that strata are within view and events decipherable. Such strata were laid down near the northwestern (Whitewater River area), southwestern (Borrego Valley area), and northeastern (Orocopia Mountains) margins of the Trough, as this part of the Gulf of California opened.

Beds deposited before the rift opening of the Salton Trough include the Imperial Formation and its lateral equivalent along the Colorado River: the Bouse

Formation. These strata are marine, lagoonal, and nonmarine (Metzger, 1968), and are here interpreted as deposited within an elongate epeiric sag formed upon continental crust before true rifting took place. The pre-Imperial-Bouse units include the Anza and Split Mountain formations on the western side of the Salton Trough and extend in age well back into the Miocene (Kerr, 1984). Volcanic flows and sills are intercalated within the Anza Formation and are tentatively dated by potassium-argon methods as between $24.8 \pm 7.4$ and $14.9 \pm 0.5$ my B.P.

The facies of the Anza and Split Mountain formations include landslide breccias with boulders up to 30 m in length, debris-flow deposits, fanglomerates, playa beds, and marine evaporites (Crowell and Baca, 1979; Kerr, 1984). They document rugged topography consisting of ranges separated by basins. Inasmuch as this topography is of Miocene age, the terrane may be part of the Basin and Range province that extended southwestward to the San Andreas fault zone, and that has been displaced by it. If so, these beds were not laid down during an early phase of the opening of the Gulf of California, but preceded it. They are also older than documented displacements on the San Andreas fault system.

Paleomagnetic measurements from some of these stratal sequences lying near the margins of the Salton Trough show marked clockwise rotations. For example, Pliocene beds in the Vallecito-Fish Creek basin on the southwest, reveal clockwise paleomagnetic rotations of as much as 35° (Johnson *et al.*, 1983), and beds in the eastern Orocopia Mountains on the northeast, even more (Terres, 1984). Other terranes may show similar rotations, but as yet, there are no data to confirm this. If paleomagnetic rotations prove tectonic rotation of blocks and terranes, perhaps similar rotations, including those involving basement blocks, have taken place during late Cenozoic times in association with displacements on the northwest-trending right-slip faults. Such rotations would have reoriented structural elements in basement terranes, such as fold axes and lineations. The present geographic orientation of structural elements may, therefore, be quite different from inferred strain orientations.

Whereas the Salton Trough is nearly infilled with sediment, basins farther southeast in the Gulf of California are not (Lonsdale, 1985). The Colorado River and its ancestors brought sediment to the Gulf that filled basins near its head, but those basins at distance from this voluminous source of detritus are widening and deepening tectonically more rapidly than they are being filled. The floors of these deep basins are receiving sediment largely by local turbidity currents. These somewhat starved basins may provide analogs to the bathyal stages of the Los Angeles, Ventura, and San Joaquin basins during "Rincon" and "Repetto" episodes in their histories (see below).

In review, this brief look at the tectonics of the Salton Trough and the Gulf of California reveals that the region is complicated; as the trough has opened, the floor has stretched irregularly, slices of the marginal rocks have moved drammatically, and some have rotated tens of degrees clockwise during their translation northwestward. Stretching and fragmentation of the continental plate have occurred along with the rising and falling of elongate slices within the transform belt leading northwestward from the Gulf of California rift constituting what I refer to as "porpoise structure" (Crowell and Sylvester, 1979; Crowell, 1981b). Some

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blocks have stood high, shedding debris from their eroding surfaces, and then have been carried laterally and downward. This pattern of mobility began in the Salton Trough region about 12 my B.P. and has been invigorated during the last 5 my. The style is overprinted upon older patterns which involve Miocene detachment faulting and structural events, and perhaps those associated with the evolution of Basin and Range structure. Even older events involve Mesozoic and early Tertiary thrusting (Engel and Schultejann, 1984).

## Comments on Pull-Apart Basins

Stretching and displacements of crustal rocks at the head of the Gulf of California follow a complex but conceptually understandable pattern. The transform faults are, in the main, subparallel, but here and there, depart from the regional trend. Where they are parallel to the direction of drift of major lithospheric plates their displacement vector is horizontal. Where the orientation of the fault surface is somewhat oblique to the plate movements, the blocks between faults may either be crowded against each other or stretched and pulled apart (Crowell, 1974b, 1985; Freund, 1982). In the right-slip transform system of general northwest trend prevailing in coastal California, where a fault trends more northerly, extension results; where its trend is more westerly, shortening results. Where the terrane is stretched, the floors of the blocks sag to make basins, and so, become receptacles for sediment washed in from nearby highlands. The stretching may extend to the point where basin floors rupture in an irregular fashion so that volcanic material wells up from depth, and dikes, sills, and irregular intrusions are emplaced within the sediments, or as flows upon the surface.

The mosaic of blocks in the broad and splintered belt leading northwestward from the Gulf of California is characterized by "porpoise structure," in which some elongate crustal blocks are arched upward and others sag downward. This is especially recognizable in the topography along the western margins of the Borrego and Imperial Valleys. Moreover, lateral displacements are great on the major faults, and are documented at tens and even hundreds of kilometers on some, such as the San Andreas, Elsinore, and San Jacinto (Crowell and Ramirez, 1979; Crowell, 1981a,b). Some blocks, while standing high, may be eroded for a time and constitute a sediment source area, and then be carried downward to form a basin floor.

Stages in the growth of pull-apart basins are illustrated by examples from several parts of California, and have features in common with those described elsewhere (e.g., Aydin and Nur, 1982; Mann *et al.*, 1983; Aydin and Page, 1984). Tiny ones occur as sag ponds along strands of the San Andreas fault zone, and may be only a few tens of meters wide and a few hundreds of meters long. Larger ones are illustrated by the Lake Elsinore depression, which is 3 by 18 km (Fig. 9-4). In these examples, the crust has been stretched within a side-stepping strike-slip fault zone, but the stretching has not proceeded so far as to allow magma to rise near to the surface. In the Lake Elsinore example, however, the stretching has been associated with asymmetric thermal uplift of the terrane, with the result that the southwestern bordering range is higher. Within the Elsinore basin, sedimentation is not quite able to keep up with tectonic stretching, so that surface drainage is impounded within the lake. Another long and narrow pull-apart basin underlies the San Jacinto Valley along the San Jacinto fault zone northwest of the city of Hemet (Fig. 9-4). It is now filled with sediment, so that surface drainage flows from it.

For pull aparts to reach sizes where the crust is completely broken so that they are floored with volcanics and lavas are intruded and interleaved with sediments, they apparently must reach dimensions of several tens of kilometers in width and many tens of kilometers in length. The actual dimensions probably depend on the thickness and structure of the crust that is fragmented and the thermal regime prevailing. These factors affect the depth and abruptness of transitions between brittle rocks near the surface and deeper ductile rocks. High Bouguer gravity values northwest of the Salton Sea and extending into the Coachella Valley and on southeastward suggest that the dimensions of this valley (15 by 35 km) are more than enough. Another example is the rhombic pull-apart basin at the head of the Gulf of California, proper (Fig. 9-1), with a size of 150 by 180 km and lying well along the continuum in size ranges. It is inferred to be a true rhombochasm (Carey, 1958), floored by volcanic rocks of oceanic affinity, and nearly filled by sediments from the Colorado River (Henyey and Bischoff, 1973). Although, as a first approximation, we can picture a spectrum of pull-apart sizes, they apparently both widen and lengthen by the incorporation of smaller basins (Aydin and Nur, 1982). Moreover, rotations take place, at least locally, as the stretching proceeds (Luyendyk *et al.*, 1980; Johnson, *et al.*, 1983).

Pull-apart basins in which volcanic material rises into an extended upper crust is one type, but other types, as well, are recognized in southern California. The crust contains subhorizontal discontinuities, some shallow and some deep, that apparently act as zones of decollement or detachment (Hadley and Kanamori, 1977; Frost and Martin, 1982; Stewart, 1983; Yeats, 1983a; Bird and Rosenstock, 1984; Crouch *et al.*, 1984; Smith and Bruhn, 1984; Cheadle *et al.*, 1986). The Garlock fault, for example, cannot be traced to depth. Two COCORP (Consortium for Continental Reflection Profiling) seismic lines across it disclose continuous reflectors at a depth of about 9 km, suggesting that it is a rather shallow feature. It is likely that many of the conspicuous strike-slip faults in the Mojave Desert and Transverse Ranges, as well as bordering regions, are also relatively shallow. Additional major structural discontinuities within basement rocks crop out in the mountains of southern California, such as the late Mesozoic–early Tertiary Vincent–Rand–Orocopia–Chocolate Mountain thrust system (Haxel and Dillon, 1978; Crowell, 1981a; Ehlig, 1982). This system and others, no doubt, occur at depth beneath valleys.

Much of southern California, therefore, consists of stacked and folded layers of basement rocks characterized by different physical properties. The basement can be viewed as made up of many allochthonous sheets of attenuated lensoid shape (Hamilton, 1982; Frost and Okaya, 1985). Some of the pull-apart basins may have opened above decollements controlled by these structural discontinuities, and are not incipient deep rifts extending downward into the lower crust or mantle. This style of basin development is especially well documented in eastern California and adjoining Arizona, where extreme crustal extension, at places associated with core complexes, has thinned the crust. Flat lenses within ductile middle curst have apparently slid apart beneath brittle higher slabs and sheets that have broken during the displacements. Shallow basins soled by listric faults extend downward into a sharp transition zone between brittle shallower structural units and ductile units below (Crittenden *et al.*, 1980; Davis *et al.*, 1980: Bally and Snelson. 1980; Gross and Hillemeyer, 1982; Hamilton, 1982). Such basins are not viewed here as deep and narrow like the Salton Trough, and Los Angeles, Ventura, and San Joaquin basins. Two "end-member" types of basins are visualized, but with many transitional types between them: (1) *volcanic-bottomed basins* that are narrow and deep, and may contain thick sedimentary packages invaded at depth by volcanics and essentially without basement floors; and (2) *detachment-floored basins* that are characterized by tilted blocks and prisms of strata and volcanic rocks laid down above decollement zones upon floors of attenuated basement slabs. This second type has not yet been recognized in western California, but the model may be applicable for some relatively shallow and small basins such as the Santa Maria, Cuyama, and Salinas (Fig. 9-1).

In discussing the Salton Trough and Gulf of California, emphasis has been placed on the tectonic and sedimentation patterns developed during the past 5 my or so in a rift environment. Events responsible for similar patterns may well have taken place during the opening and early histories of some late Cenozoic basins to the west in coastal California. It is reasonable to ask the question: Did the Los Angeles, Ventura, and San Joaquin basins go through somewhat similar stages early in their histories?

## LOS ANGELES BASIN

Among the late Cenozoic basins near the California coast, the Los Angeles basin (Fig. 9-5) is one of the best known in view of its prolific oil production. It is only 60 km long and 45 km wide, yet contains over 7000 m of Upper Miocene and younger sedimentary rocks, and a huge, but unknown thickness of older beds in its deepest part (Yerkes *et al.*, 1965; Harding, 1973; Mayer, this volume). For its size, it is the world's most prolific oil producer (Gardett, 1971), and can be expected to ultimately yield more than 12 billion barrels. Most of the oil and gas is produced from strata younger than Middle Miocene, from sediments laid down within the basin or around its margins as it grew and deformed. Obvious questions include: Why is this small basin so productive? What geologic circumstances in its history are responsible?

The rocks in the region of the Los Angeles basin can be considered as those constituting the framework exposed around the basin and near its margins. those deposited within the basin itself, and those deemed to lie beneath its deep and irregular floor. At present, because the floor of the basin is inaccessible by drilling, we can only infer what it is like on the basis of the interpretation of sparse geophyysical information, and by applying tectonic and sedimentation models. One of the purposes of this paper is to speculate on the character of deep structure

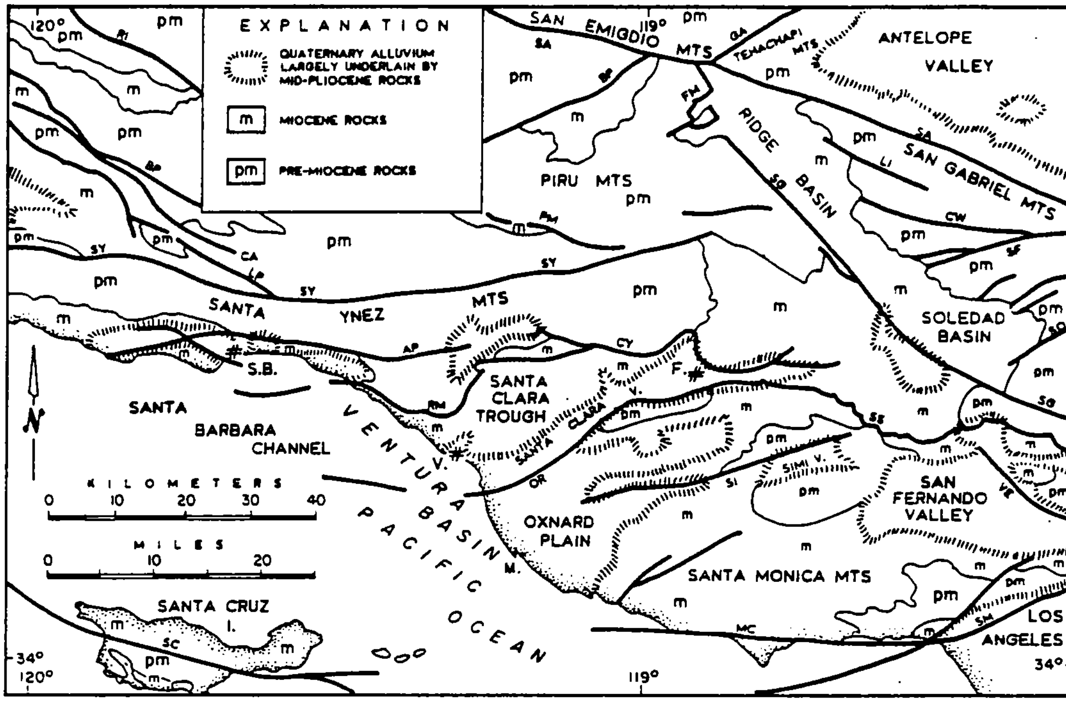


Fig. 9-5. Sketch map of Los Angeles basin and Santa Monica Mountains region. Faults: CH, Chino; CU, Cucamonga; EL, Elsinore; MA, Sierra Madre; MC, Malibu Coast; NI, Newport Inglewood; OR, Oak Ridge; PV, Palos Verde; RA, Raymond Hill; SA, San Andreas; SG, San Gabriel; SI, Simi; SJ, San Jacinto; SM, Santa Monica; VE, Verdugo; WH, Whittier. Base from Jennings *et al.* (1977).

beneath the Los Angeles and other basins by extrapolating concepts from elsewhere, including those from the Gulf of California region described briefly above.

Sedimentary terranes surrounding the Los Angeles basin have been reasonably well mapped, but the basement and volcanic rocks still need investigation utilizing modern methods. Neogene and Quaternary strata display sharp facies changes around the margins and into the basin, and demonstrate that sedimentation took place concurrently with basin evolution. Inasmuch as the geology of the region has been studied for three quarters of a century, understanding of depositional and tectonic processes in the Los Angeles basin has moved forward concurrently with improvement in our concepts of sedimentation and structure in general. In fact, this is one of the regions where the concepts of turbidity currents and strike-slip faulting evolved. Despite the large amount of surface and subsurface information available, however, new viewpoints and methods have not yet been fully exploited in working out its tectonic history. For example, only within the past few years have paleomagnetic data become available in the Santa Monica Mountains and some areas bordering the basin (3.g., Kamerling and Luyendyk, 1979; Luyendyk *et al.*, 1980; Luyendyk and Hornafius, this volume). Geologists now face the challenge of fitting these data into syntheses, but more paleomagnetic data at critical sites are needed. Many new approaches (geological, geochemical, geophysical, and paleontological) are now available and need to be applied to the region. Geohistory plots (see Mayer, this volume) for deep wells are not widely available. Although coastal California is now recognized as made up of a mosaic of far-traveled and mobile blocks of unknown thickness that have moved both short and long distances at different times (Howell *et al.*, this volume), and rotated as they have moved, these concepts have not as yet been adequately investigated and applied to the Los Angeles region.

Basement rocks, Cenozoic and older, crop out around the margins of the Los Angeles basin in the Transverse Ranges, Peninsular Ranges, and nearby Mojave Desert (Dibblee, 1967; Burchfiel and Davis, 1981; Ehlig, 1981; Gastil, *et al.*, 1981). Deeply eroded arc rocks are now represented by granitic terranes, largely of Late Cretaceous age. These terranes include huge thrust faults now folded and dismembered, such as the Vincent thrust system (Ehlig, 1982). Basement rocks found to the west of the Los Angeles basin, and penetrated by wells west of the largely buried Newport-Inglewood fault zone, consist of greenschist, gabbro, and small masses of other types, including blueschist. Some of these intricately deformed metamorphic rocks are interpreted as having formed within an acretionary wedge during Mesozoic plate convergence (Platt, 1975; Howell and Vedder, 1981; Vedder *et al.*, 1983). Parts of these terranes are viewed as having travelled to great depths down subduction zones (Crowell, 1968). The basement here is overlain unconformably by Upper Cretaceous and younger strata mainly consisting of clastic sediments laid down in a series of depressions lying within a forearc basin (Dickinson, 1981b). Some of these terranes on the west have probably been brought in from great distance by lateral movements and are now sutured to the continent (Coney *et al.*, 1980; Vedder *et al.*, 1983; Schermer *et al.*, 1984; Howell, 1985).

It was this heterogeneous terrane, already consisting of a collage of far-traveled blocks welded to the margin of continental North America, that was stretched and fragmented in mid-Tertiary time to make the Los Angeles basin. We, therefore, need to distinguish clearly between two sequences of rocks: those formed and emplaced previous to the origin of the basin and those younger packages deposited within the Los Angeles basin itself. The stretching, followed by fragmentation and block rotations, occurred some time after the arrival of the East Pacific Rise off the coast (Fig. 9-2; Atwater, 1970). The Los Angeles basin, along with several others both onshore and offshore, originated during this event as well, but presumably not completely simultaneously. Nonetheless, the Los Angeles, Ventura, and southern San Joaquin basins all were born at nearly the same time, about 22 my B.P. (see below).

The margins of the Los Angeles basin have been grossly modified by tectonic events superposed after the basin originated. Pre-mid-Miocene rocks, at places, crop out and dip toward the basin center, and afford an opportunity to decipher events occurring just before and during basin formation. For example, at its southeastern margin, a prism of strata encompassing beds from Late Cretaceous to Middle Miocene in age is exposed in the San Joaquin Hills and Santa Ana Mountains. These beds can be traced in the subsurface toward the northwest and beneath younger strata (Yerkes *et al.*, 1965). Some faults within the San Joaquin

Hills have been intruded by mid-Miocene volcanics (Vedder *et al.*, 1957), dated at between 15 and 13 my (T. L. Wright, E. S. Parker, and R. C. Erickson, 1973, and personal communications, 1973), showing that movement had occurred before that time. Volcanic rocks of about this age are widespread in the basin and have been reached by many wells (Vedder *et al.*, 1957). Moreover, upper Middle Miocene strata overlap these faults unconformably, showing that displacement on them has not recurred since that time. These welded faults document an episode of fragmentation or rifting, and the volcanic rocks within the basin at depth suggest volcanic upwelling as the basin floor stretched (Crowell, 1974b, 1976). The younger sediments document later infilling of the basin and overlapping onto the margin.

Sediments first deposited within the incipient basin are now viewed as overlapped and occurring as stretched, attenuated, and fragmented units in the deepest part of the basin. These older basinal beds, considered here as disrupted during a later rifting phase, are now well below the deepest drill holes. The top of the Miocene lies below 5600 m at the basin center, a few kilometers south of the civic center of Los Angeles (Harding, 1973). It is unknown how thick the older sediments and associated volcanics are in the deepest part.

I speculated in 1976 that the western Santa Monica Mountains might be the northwestern part of the Los Angeles basin, displaced far to the west by the Malibu Coast–Santa Monica fault system and much uplifted and deeply eroded in Late Pliocene to Recent time (Fig. 9-5) (Crowell, 1976). This hypothesis fitted with those of Sage (1973) and Campbell and Yerkes (1976), in which they argued for up to 90 km of left slip on this fault system, a system that trends approximately east-west. The geology of the Santa Monica Mountains is complex and much controversy has flourished concerning stratigraphic and structural relations and interpretations (e.g., Durrell, 1954; Campbell *et al.*, 1966; Truex, 1976, 1977; Yerkes and Campbell, 1980; Dibblee, 1982). Durrell, Truex, and Dibblee recognize mainly high-angle faults, whereas Campbell and Yerkes recognize, in addition, low-angle and folded detachment faults. During the past decade, rotation data from paleomagnetic studies (Kamerling and Luyendyk, 1979; Luyendyk *et al.*, 1980; 1985; Luyendyk and Hornafius, this volume) and interpretations from paleocurrent investigations (Link *et al.*, 1984) suggest that the regional tectonic history and the relations of the Santa Monica Mountains block to neighboring blocks are complicated. If the terrane of the western Santa Monica Mountains ever was adjacent and part of the Los Angeles basin, and the paleomagnetic data truly indicate rotations of up to about 90° between the mountain block and the basin, then rotations and major strike-slip faulting both have played roles in bringing it to its present position. As yet, the faults responsible for these displacements are not identified. The hypothesis in this simple form is, therefore, no longer quite so attractive, and yet, Miocene rocks exposed in the Santa Monica Mountains are, indeed, the kind that I would expect to occur beneath both the Salton Trough and the Los Angeles basin. The Middle and Upper Miocene rocks of the Santa Monica Mountains consist of deep-water turbidites interbedded with mudstone, and stretched and intruded by diabasic sills and dikes between 17 and 12 my B.P., averaging about 15 (Yerkes and Campbell, 1980; Weigand, 1982). Some of the dikes are interpreted as feeders to submarine flows exposed near the top of the

Middle Miocene section. From these relations, I infer that the basin floor subsided during stretching and partial disruption, as magma worked its way upward. Many of the controversial complications may be related to these disruptive processes that occurred hand in hand with volcanism and sedimentation. Huge slide blocks and detachment faults fit into such a speculative history.

During Early Miocene time (from about 22 to 16 my B.P.), faults along the Newport-Inglewood zone bordered the Los Angeles basin on the west and southwest. Here, fans of the San Onofre Breccia extended from uplands on the southwest into the basin (Stuart 1976, 1979). These uplands were underlain by Catalina Schist, a metamorphic complex interpreted as formed during plate convergence within an accretionary prism during Mesozoic times (Platt, 1975). This source terrane was emplaced and uplifted, and covering rocks were removed by erosion by the time the San Onofre Breccia was deposited (Woodford, 1925; Stuart, 1979). Although the Newport-Inglewood zone is a major fault zone or suture, its origin and history remain unclear (Hill, 1971a; Yeats, 1973; Barrows, 1974; Platt and Stuart, 1974). Basement rocks contrast across it, and no Mesozoic or Paleogene strata are recognized on the block just west of the fault zone. Displacements during Early and Middle Miocene time resulted in significant dip separations along the fault belt at the southwestern margin of the Los Angeles basin. These dip separations may have resulted from major strike slip, where blocks on either side of such a fault alternately stood high or low, but proof of major strike slip of the basement rocks across the Newport-Inglewood zone is lacking.

If the Newport-Inglewood zone experienced major strike-slip during the Early and Middle Miocene, its continuation to the northwest within or beneath the Transverse Ranges has not been identified. Perhaps its continuation has not been recognized because later dismemberment of the region and subsequent rotation of crustal blocks have removed the hypothesized northwestern extension (Luyendyk *et al.,* 1980), or speculative plate-tectonic reconstructions may allow the fault to end abruptly where plate movements sidestep to other faults (Campbell and Yerkes, 1976). In fact, the kinematics of block rotations permit the termination of such a fault at the edge of a rotated terrane (Luyendyk *et al.,* 1980). As yet, however, the tectonic significance of the east-west-trending series of faults between the Los Angeles basin proper and the Transverse Ranges remains enigmatic. These include the Malibu Coast, Santa Monica, Raymond Hill, Sierra Madre, and Cucamonga; they have been active at different times and places with different senses of slip, perhaps, in part, because they constitute the margin of a rotated block, now on the north. Basement terranes separated by this string of faults are very different, and it is not yet known when or how they were emplaced. In my view, no tectonic belt in southern California is more perplexing.

Within the Los Angeles basin, a belt along the Newport-Inglewood zone is active today, as shown by Recent fault scarps, warped river and marine terraces, growing folds, and earthquakes (Barrows, 1974). Although it was especially active during Early and Middle Miocene time, it also may mark a suture between a far-traveled block on the west that was brought against the continental terrane in early Tertiary time or previously (Vedder *et al.,* 1983). It has, therefore, had a long history under quite different tectonic regimes.

Geologic relations in the region bordering the Los Angeles basin on the north and west bear on the acceptability of part of the tectonic model for coastal southern California proposed by Luyendyk *et al.*, (1980; 1985), and Luyendyk and Hornafius (this volume). On the basis of paleomagnetic data, they conclude that the Santa Monica Mountains block and a different block including Catalina Island, rotated about 70° clockwise during the Miocene Epoch, with most of the rotation taking place between 15 and 5 my B.P. (Hornafius *et al.*, 1986). Paleocurrent and sediment-source studies within the Santa Monica Mountains (Crowell, 1957), and within Cretaceous strata of the Simi Hills (Link *et al.*, 1984), considered as joined to the Santa Monica Mountains block, show derivation from the south. If the block is conceptually "unrotated," provenance souces for the Cretaceous beds match reasonably satisfactorily with similar facies and underlying basement rocks in the Santa Ana Mountains–Peninsular Ranges region. Link *et al.* (1984, Fig. 22) restore the Cretaceous beds by both undoing the rotation and displacing the regions sinistrally along the Malibu and related fault zones (also, see Yeats, this volume). Although this interpretation seems reasonable, and has been advanced as independent confirmation of the rotations, not enough is yet known concerning how large and how deep are the rotated blocks and the detailed timing of the rotations. In addition, the structure and stratigraphy of the Santa Monica Mountains themselves are still confusing, and there is also not enough known concerning paleocurrents, sediment provenance, and the role of the Malibu Coast–Santa Monica fault zone.

The stratal packages of the Los Angeles basin and its margins are usefully conceived of as: (1) pre-basinal or pre-rift; (2) syn-basinal or syn-rift; and (3) post-rift (but also basinal). The pre-basinal rocks include all of those older than Early Miocene: the basement rocks and overlying strata from Cretaceous through lower Tertiary, up through the Sespe and Vaqueros formations of Oligocene and Early Miocene age. During Oligocene time, nonmarine sedimentation prevailed at the site of the future Los Angeles basin because of tectonic uplift (Glazner and Loomis, 1984; Nilsen, 1984a), which was reinforced by a strong eustatic drop in sea level (Hardenbol *et al.*, 1982; also, see May and Warme, this volume). The trends and depocenters of these pre-basinal strata are unrelated to those of the Los Angeles basin, although they probably influenced its shape.

The syn-basinal sequence was deposited gradationally after the transgressive Vaqueros Formation was laid down near the beginning of the Miocene Epoch, during a time of crustal stretching, attenuation, and subsidence. This unit was followed in late Early Miocene by deposition of the marine Topanga Formation, which included marine tongues of the San Onofre Breccia extending basinward from the southwestern margin where near-source nonmarine facies occur locally (Stuart, 1976). Stretching had evolved into rifting, so these strata may be termed syn-rift, but these syn-rift sediments are, therefore, younger than syn-basinal units, of which they are a part. The southwestern side was demarcated along a sharp fault boundary on the southwest by prisms of the coarse San Onofre Breccia. Faulting, suggesting a rift phase, followed very quickly upon the deposition of the immediately underlying Vaqueros Formation, so there was only a short interval of basinal sagging before rifting. The San Onofre Breccia and the Topanga

Formation grade laterally into units of siliceous shale, assigned to the Monterey Formation. Much of the basin during Middle Miocene time lay at moderate depths, sheltered from the influx of coarse debris, except within submarine canyons and their subsea fans. Upper Miocene strata of Monterey affinities transgress across fault zones, such as the Whittier and Chino, and extend well into the San Gabriel Valley, Puente Hills, and the Pomona area.

Beginning anew in latest Miocene time and then sharply in the Early Pliocene (corresponding with deposition of the Repetto Formation), the basin floor subsided to bathyal depths (Ingle, 1981a). This implies that strong stretching and thinning of the crust took place (McKenzie, 1978; Turcotte and McAdoo, 1979), and that the influx of sediments from surrounding source areas was unable to keep pace with the rapid subsidence. The Gulf of California rift disrupted continental rocks at about the same time as Repetto subsidence in the coastal regions, and the San Andreas fault system readjusted in the Big Bend region to the north. Displacment switched from the San Gabriel fault as the principal strand to the modern San Andreas (Crowell, 1982).

During the Pliocene, and continuing to the present, the Newport-Inglewood zone was rejuventated so that en-echelon anticlinal hills formed on the sea floor along it (Harding, 1973; Wright *et al.*, 1973). This topography guided turbidity currents between anticlinal hills and into synclinal troughs. Continued folding of uptilted sand-filled channels at places has determined the location and shape of some oil traps. Around the basin margins, moderate deformation has continued throughout the Pliocene and Quaternary, and continues today. The basin filled so that nonmarine alluvial fans stretch across it to the sea on the west, and streams carry debris westward to reach offshore basins.

In summary, the Los Angeles basin originated about 22 my B.P., followed by rapid rifting about 16 my B.P. Slow deepening ensued until about 5 my B.P., when rapid subsidence resulted from sharp renewed rifting. Since then, subsidence has continued more slowly along with sedimentation and deformation, and the basin is now filled.

## VENTURA BASIN

The Ventura basin, and its associated offshore extension westward beneath the Santa Barbara Channel, also originated in Early Miocene time (about 22 my B.P.) as the result of crustal stretching and subsidence (Fig. 9-6). Subsidence was more rapid than sedimentation, so that the floor quickly reached bathyal depths (Rincon Formation) (Finger, 1983). The basin has an east-west orientation today, and abuts on the east against the San Gabriel fault. The region now occupied by the basin has an involved history, in part similar to that of the Los Angeles basin, but with some episodes different and still ambiguous. In fact, over the decades, there has even been controversy concerning the definition of the Ventura basin, as tectonic mobility and patterns of sediment deposition have become documented.

Pre-basinal strata, or those older than Miocene, were laid down under different tectonic controls, and are, therefore, not included here as part of the



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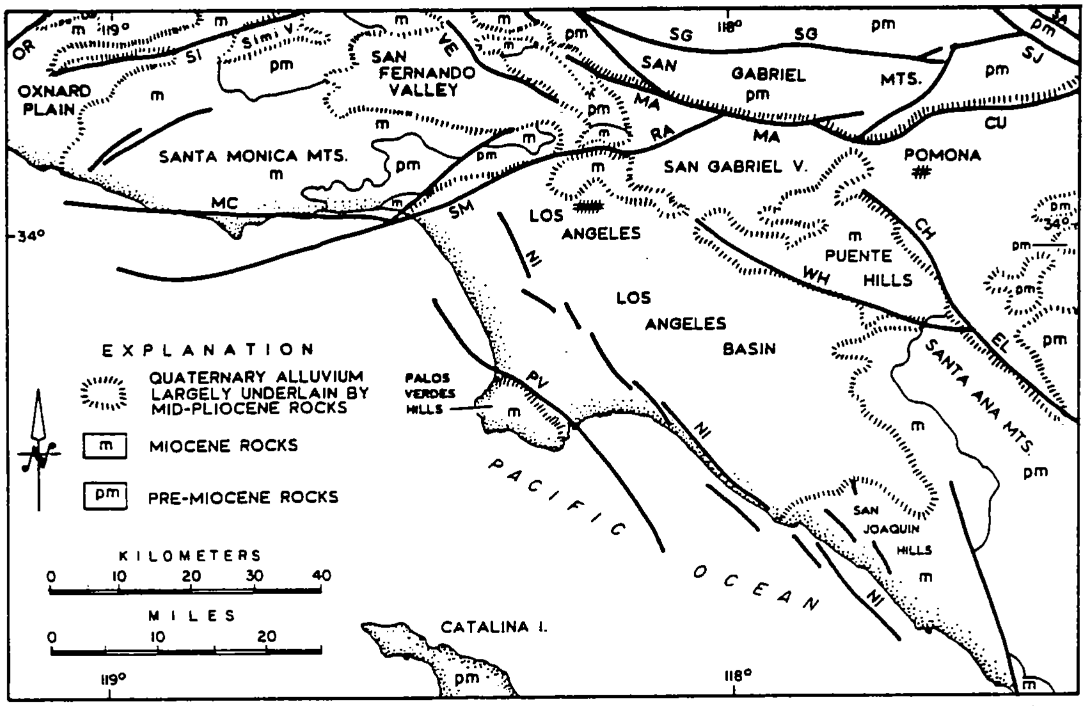


Fig. 9-6. Sketch map of Ventura basin and vicinity. Faults: AP, Arroyo Perida; BP, Big Pine; CA, Camuesa; CW, Clearwater; CY, San Cayetano; FM, Frazier Mountain; GA, Garlock; LI, Liebre; LP, Little Pine; MC, Malibu Coast; OR, Oak Ridge; PM, Pine Mountain; RI, Rinconada; RM, Red Mountain; SA, San Andreas; SC, Santa Cruz; SF, San Francisquito; SG, San Gabriel; SI, Simi; SM, Santa Monica; SO, Soledad; SS, Santa Susana; SY, Santa Ynez; VE, Verdugo. Cities: F, Fillmore; S.B., Santa Barbara; V, Ventura. M, Mugu Submarine Canyon. Base from Jennings *et al.* (1977).

Ventura basin. For example, the thick sequence of Paleogene strata lying within the Santa Ynez Mountains that now rims the basin on the north, were laid down, according to present concepts, within an irregular forearc basin. Paleomagnetic data suggest that the crustal block containing the range has since been rotated about 90° (Hornafius, 1985; also, see Luyendyk and Hornafius, this volume). Near the northeastern corner of the basin, Neogene beds lap across Oligocene and older rocks, including pre-Cretaceous basement. On the east as well, younger beds of the Ventura basin lap across the San Gabriel fault and extend eastward beyond it for another 10 km; older beds, originally part of the eastern Ventura basin, have been truncated and offset (Crowell, 1952a, 1960, 1962; Carman, 1964; Ehlig *et al.*, 1975). The Neogene basin, therefore, has had different shapes and sizes at different times because deformation and major displacements on some faults have occured as the beds accumulated.

The central part of the Ventura basin and its southern margin also show changes in shape and position through time, and not all changes have yet been satisfactorily demarcated. In Middle and Late Miocene time (between about 14 and 6 my B.P.), the Ventura basin was wider, and also more irregular in shape, with several local depocenters. On the east, a sub-basin lay near the San Gabriel fault, and began to be transected by fault displacements beginning about 12 my B.P. (Crowell, 1982). Beds laid down 14–6 my B.P. consist largely of units of the Monterey Formation and include diatomaceous members made up of laminated strata deposited in protected and moderately deep water. Such deposits lapped across a subsea shoulder or ridge with seaknolls along it, which is now uplifted to form Oak Ridge (Yeats, 1965, 1983a, this volume; Nagle and Parker, 1971; Crowell, 1976). They extend southeastward into the Simi Valley and San Fernando Valley regions, and into the area of the Santa Monica Mountains. How the Late Miocene Ventura basin joined with the Los Angeles basin is still unclear in view of incomplete information on roles of tectonic rotations and the Malibu Coast fault. In addition, the tectonic history of the Channel Islands must also be clarified: Miocene rocks on some of them also reveal marked rotations (Kamerling and Luyendyk, 1979; Luyendyk *et al.*, 1985).

The Santa Clara trough evolved as a narrower part of a broader Ventura basin in latest Miocene time. Its origin was heralded by rapid subsidence; the sea became about 2000 m deep by the Early Pliocene (Repetto) (between 5 and 3 my B.P.) (Ingle, 1981a). It deepened and reached eastward as a narrow wedge-shaped trough, with the eastern point near Fillmore. Turbidity currents sluiced down its axis and along its floor to depositional sites in the Pliocene Santa Barbara Channel. Steep canyons notching the northern margin brought coarse debris to the trough floor, including fragments of indurated Monterey Shale, only recently deposited and lithified. Differential extension, wide on the west with a hinge on the east, apparently accounted for its sphenochasmic shape. Sedimentation rates during trough filling were remarkable, and reached values greater than 2000 m/my (Yeats, 1977, 1978).

During Pleistocene time, the Santa Clara trough was compressed in a roughly northwest-southeast direction, and tectonic inversion of the floor of the trough was the consequence. Before this severe shortening, the floor of the trough lay at bathyal depths (Finger, 1983), and turbidity currents funneled westward along its deep axis. As a result of the closing of the trough and squeezing, bundles of turbidite sandstones were uplifted into the crestal areas of the Ventura Avenue anticline and within other anticlines along the same tectonic trend (Crowell, 1976). As this tectonic inversion took place, detachment or décollement probably occurred at depths of about 5 km, so that the anticlines may not be rooted (Yeats, 1983a). An explanation of how regional shortening occurred below the level of structural decoupling is lacking and puzzling. In the future, deep reflection-seismic profiling across and below the level(s) of décollement may help solve this enigma. Is it possible that this level of structural disconnection is the same as that at the diffuse base of crustal blocks showing rotation based on paleomagnetic and other data? Are there several such levels? Is it conceivable that crowding together and uplift of these blocks within the central Transverse Ranges took place as the northwest end of the Gulf of California widened and the Big Bend of the San Andreas system became more pronounced? To what extent has the jostling of blocks, differentially moving on a deep level of sharp transition from brittle behavior of the rocks above to ductile below, been responsible for this mobile scenario?

Today, the shape of the Ventura basin is quite different. The Santa Clara trough is closed and filled with a thick section of marine beds capped by a veneer of nonmarine strata extending well to the west. Most of the coarse sediment brought to the shore of the Santa Barbara Channel at present works its way southward in longshore drift to the Mugu Submarine Canyon (Crowell, 1952b).

From the viewpoint of providing information on what has happened at depth, it is fortunate that Pleistocene movements have been accompanied by great uplift and deep erosion in the Transverse Ranges, so that older rocks and their structure have been brought into view at the surface (Fig. 9-2) (Jackson and Yeats, 1982). Rapid uplift and erosion are continuing vigorously as the coastal region of the Santa Barbara Channel shortens and rises, while regions farther west stretch and subside (Yeats, 1977; Keller *et al.*, 1982b; Lajoie *et al.*, 1982b; Rockwell *et al.*, 1984). In fact, near the axis of the growing Ventura Avenue anticline, the region is now rising at a rate of about 7 mm/y. Most of the oil within the huge Ventura Avenue Oil Field has migrated into it during the last few hundred-thousand years.

## SAN JOAQUIN BASIN

The southern part of the San Joaquin Valley is another deep Neogene basin, which has both infilled and deformed through time, up to and including the present (Fig. 9-7). It underlies the southern fifth of the Great Valley of California, which includes both the San Joaquin and Sacramento Valleys. Surface drainage at the southern tip of the valley comes from both the Sierra Nevada and the central Transverse Ranges, and fails to join rivers flowing to the ocean today. Instead, water is impounded from time to time in broad and shallow lakes, such as Buena Vista Lake. Active deformation and sedimentation control the shape of the landforms.

Most of the Great Valley to the north of the southern sub-basin is underlain by Paleogene and older strata beneath a veneer of Quaternary alluvium. These beds were laid down in depocenters along a forearc basin associated with lithospheric-plate convergence (Ingersoll, 1979). In the southern part of the San Joaquin Valley, Neogene strata thicken into an irregular basin that enlarged through time (Zieglar and Spotts, 1978; Graham and Williams, 1985), probably beginning about 20 my B.P., during deposition of the Temblor Formation. This was followed by rapid deepening about 16 my B.P. and the deposition of the Monterey Formation. The thickest section, aggregating at least 12 km is so thick that little is known, I believe, concerning the sedimentary facies and age of the presumed rift series at the bottom of the sub-basin. The center of the deep hole is only about 20 km north of the southern border, where Eocene beds today lie unconformably upon Cretaceous and older granitic and metamorphic basement at more than 2000 m above sea level! This is, indeed, a remarkably steep structural gradient, which includes a sharp break across the largely buried White Wolf fault (MacPherson, 1978; Webb, 1981; Bartow, 1984). Significantly, within the Temblor Range on the

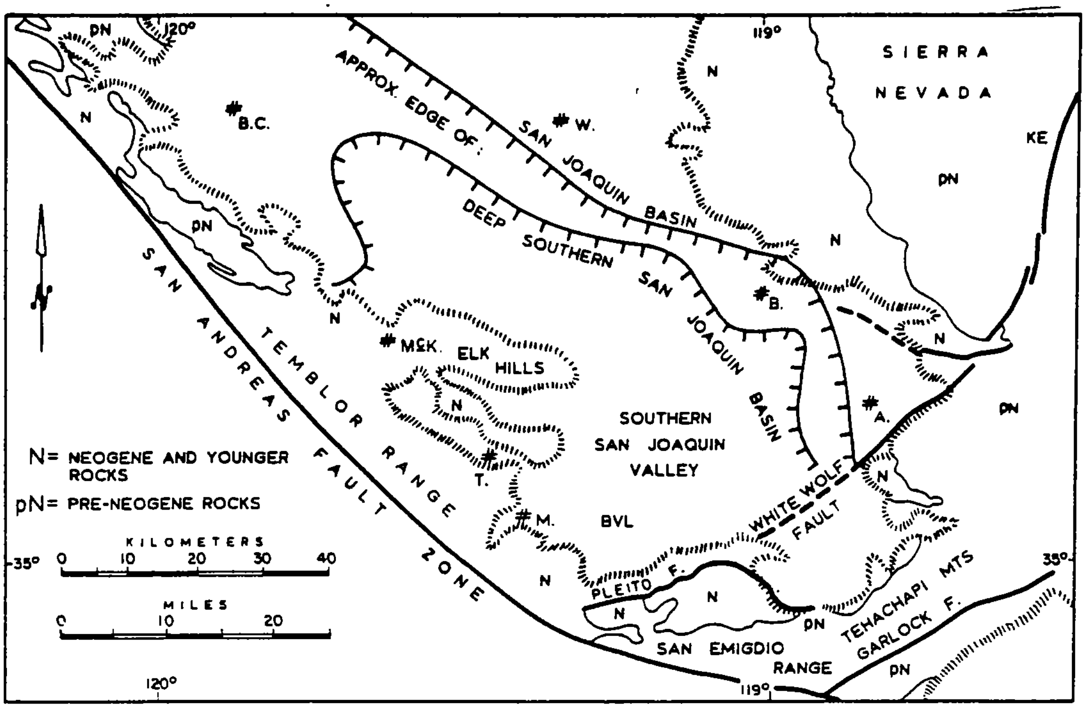


Fig. 9-7. Sketch map of southern San Joaquin Valley and environs. BVL, Buena Vista Lake. Towns: A, Arvin; B, Bakersfield; B. C., Blackwell's Corner; M, Maricopa; McK, McKittrick; T, Taft; W, Wasco. Base from Jennings *et al.* (1977).

west, no Cretaceous or older rocks are known, nor have they been reached by the drill, so far as I know. Strata of the Franciscan Complex, Great Valley Group, and Paleogene Series are not reached in this region, and, if present, must lie at depths greater than 9 or 10 km. It seems more likely that they are severely attenuated and fragmented at these depths as the consequence of crustal stretching during late Early Miocene time, shortly after the basin originated. This stretching and fragmentation is pictured as having been accompanied by deep subsidence during the time when thick sequences of diatomaceous shale and interbedded sandstone of the Temblor-Monterey sequence (including the Maricopa Shale) were deposited.

The eastern margin of this Miocene sub-basin is demarcated by Miocene beds that grade from continental into marginal marine (Bartow, 1984; this volume). South of the White Wolf fault, which probably became active during the latest Miocene, the margin trends more southwesterly and then westerly, but displacement on the fault and perhaps oroclinal bending of the southern block may be responsible for its present orientation. Paleomagnetic data from the southern Sierra Nevada, to the east of the Miocene basin, suggest clockwise rotations of about 45° (Kanter and McWilliams, 1982; McWilliams and Li, 1985). These data, however, come from Cretaceous plutonic rocks nonconformably beneath Miocene



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volcanic rocks dated at about 16 myBP, and the Miocene rocks are not rotated. The rotation, therefore, took place during the interval between about 80 and 16 my B.P. Kanter, McWilliams, and Li suggest that the rotation occurred in the early Tertiary, but it seems as likely to me that it was associated with the tectonic opening of the sub-basin not long before 16 my B.P. In fact, the "tail" of the Sierra Nevada, which includes the Tehachapi and San Emigdio Mountains, is cut by faults of several ages (not shown on Fig. 9-7), and the basement rocks are broken and locally shattered (Crowell, 1964; Ross, 1980, 1984).

Eocene and Oligocene beds along the northern flank of the San Emigdio–Tehachapi Mountains display facies showing that water depths increased from shallow on the east to bathyal on the west (Nilsen *et al.*, 1973). These beds now stand nearly vertically, so that the map view is essentially a cross section. Deep-water facies are on the west, and continental deposits on the east. Uptiliting of the sequence along the flank of the mountains in Quaternary time would account for the facies relations appearing on the map commonly referred to as the "tail of the Sierra Nevada." According to this view, Pliocene and Quaternary uplift and deep erosion would account for the "tail" without rotation. This is another region where we need additional work.

In Early Miocene time (between about 20 and 16 my B.P.), however, the sub-basin opened westward. It has since been truncated and offset about 300 km by the San Andreas fault (Addicott, 1968; Huffman, 1972; Graham and Williams, 1985). The deep basin is, therefore, older than the San Andreas proper in this region and older than most of the sliding of the Salinia block northwestward across its western part during Late Miocene time. The crustal fragmentation and subsidence responsible for the basin are older than displacements on the San Andreas fault proper, the fault zone so conspicuous today. The western offset part of the Early Miocene basin, now dismembered and overprinted and probably tectonically rotated, lies in the Santa Cruz Mountains–Monterey Bay regions (Hill and Dibblee, 1953; Nilsen, 1984a). Faults such as those belonging to the Red Hills–San Juan–Chimineas system, now within the Salinia block, may have played a part in the offset of the basin's western part (Johnson and Normark, 1974; Smith, 1977; Graham, 1978; Crowell, 1979; Page, 1982b).

The southwestern margin of this deep Miocene sub-basin is presently formed by the nearby San Andreas fault, and in Miocene time (between about 12 and 7 my B.P.), appears to have been controlled by deformation along it. During this interval, a granitic high, interpreted to be the Salinian block, moved northwestward across the basin, thus shutting off part from straight-line access to the Pacific Ocean on the southwest. The block southwest of the fault zone was uplifted and provided a source for turbidite sands (upper parts of the Stevens Sand) flowing into the basin (Webb, 1981). Previous to this time and continuing to the end of the Miocene, however, most of the sand came down submarine canyons in the Sierra Nevada region on the east and northeast. The debris then flowed northwesterly down the axis of this mid-Miocene trough. During these times, however, folds were growing along the western margin of the basin, in part as the result of simple shear on the developing San Andreas transform system (Harding, 1976; Crowell, 1985). The turbid underflows carried sediment along synclinal valleys and through saddles in growing anticlinal hills, to flood bathyal plains. The deepest part of the basin at this time was not adjacent to the San Andreas zone, but to the northeast. The region of the Temblor Range was undergoing deformation, as shown by facies and thickness changes and unconformities. The region of the range stood high enough above the depths to form a barrier on the southwest, presumably because of deformation and tectonic thickening of the strata. These tectonic events probably occurred between about 15 and 12 my B.P.

During the Pliocene and Quaternary (including the present), uplift and deformation have taken place in the southern Diablo Range and its continuation southeastward into the Temblor Range. The late timing of this uplift is shown dramatically by landforms along the southwestern margin of the San Joaquin Valley and by the occurrence of the Arvin-Tehachapi Earthquake of 1952 and the Coalinga Earthquake of 1982 (Oakeshott, 1955; Bennett and Sherburne, 1983; Rymer and Ellsworth, 1985).

Geological relations within the San Emigdio Range bear on this reconstruction. Uplift and deep erosion in this region are also very recent geologically (Davis and Duebendorfer, 1982), and the basement includes ophiolotic rocks similar to those of the foothills of the Sierra Nevada. Perhaps, they have been brought westward by oroclinal bending in mid-Miocene time and before displacements on the White Wolf fault (Ross, 1980; McWilliams and Li, 1985), but they may have been exposed largely as the result of uplift and deep erosion. These events are viewed here as having taken place after the origin of the deep Maricopa sub-basin, and are pictured as having partly closed it again, but along its southern margin. The closing culminated with the accentuation of the "Big Bend" of the San Andreas fault during the Quaternary. Displacements on several other faults in the region, such as the Garlock, Pleito, Frazier Mountain, Abel Mountain, and Big Pine, took place concurrently.

In review, the Maricopa sub-basin probably originated in Early Miocene time as the result of crustal attenuation and fragmentation. Pre-Miocene rocks were broken during this event, so that at many places, they are probably no longer preserved beneath the very thick sequence of Miocene and younger beds that subsequently filled the irregular hole. In early Late Miocene time, activity on the San Andreas fault zone began to truncate the basin on the southwest and began to displace part of it far to the northwest. During this stage, strata along its southwestern margin were tectonically thickened. Sand was carried into its trough from both the Salinian block across the fault on the southwest and from basement terranes to the east and south. By the end of the Miocene, tectonic closing of the sub-basin was underway. It became isolated at the beginning of the Pliocene and is now topped off with nonmarine deposits of Pliocene and Quaternary age. Deformation, accompanied by sedimentation with sharp facies changes, continues vigorously today.

## OTHER BASINS

Several other Neogene basins in onshore California have histories similar to those described above, but they are not dealt with in detail here. The Cuyama basin

(Fig. 9-1) lies to the west of the southern end of the San Joaquin Valley (Lagoe, 1984; this volume). It originated about 20 my ago with strong subsidence following deposition of the Lower Miocene Vaqueros Formation. After the latest Miocene, nonmarine deposition prevailed, and Pliocene deepening was not significant. A similar history approximately fits the Salinas basin to the northwest (Graham, 1978).

The Santa Maria basin (Fig. 9-1) opens westward to the present Pacific Ocean, but its margin is not far offshore. The basin is now the site of active oil exploration, so that much new information is being acquired and it is premature to comment on its tectonic history until these data are available. For both regional and tectonic discussions, refer to Hall (1981a,b). The Huasna basin, adjoining the Santa Maria basin proper on the northeast, is a deformed pull apart with superposed structures fitting the simple-shear scheme (Kablanow and Surdam, 1983).

Ridge basin (Fig. 9-6), a small Miocene basin born about 12 my B.P. within the central Transverse Ranges, is of significance because it has been uplifted during Quaternary time and deeply eroded, so that relations between sedimentation and tectonics are on display (Crowell and Link, 1982). Similar relations are expected along the margins of other basins, but are deeply buried and out of sight. In Ridge basin, for example, right slip has occurred along with sedimentation, so that about 12 km of strata have been laid down within a moving depocenter. This depocenter is pictured as having moved adjacent to slowly uplifting source areas. The resulting thick sequence consists of a shingled stack of strata about 12 km thick when the thickness is measured across bedding, but the vertical thickness at any one place is not more than a third of this total.

It is likely that a similar shingling mechanism has operated along the southwestern margin of the southern San Joaquin basin, but the mechanism is more easily documented for Ridge basin. For the San Joaquin basin, during latest Miocene time (Santa Margarita), coarse conglomerates were laid down in the region of the Temblor Range (Dibblee, 1973a) from source areas in the Salinian block. Sands carried down submarine canyons from Salinia, fed the youngest units of the Stevens Sand within the depocenter (Webb, 1981). As displacement accumulated on the San Andreas fault, the source area moved laterally alongside of the depocenter, perhaps strewing sediments in a similar shingling style. A similar style of deposition is plausible for the San Onofre Breccia along faults bordering the Los Angeles basin on the southwest, and perhaps other basins in the offshore region of southern California.

## DISCUSSION

The histories of the California onshore basins considered briefly above suggest an evolutionary sequence. The Salton Trough and basins within the Gulf of California, only 5 my or so in age, suggest characteristics of an early stage, and the Los Angeles, Ventura, and San Joaquin basins add insights because they have undergone additional stages. Tentatively, I suggest some of the stages in their evolution (Fig. 9-8):

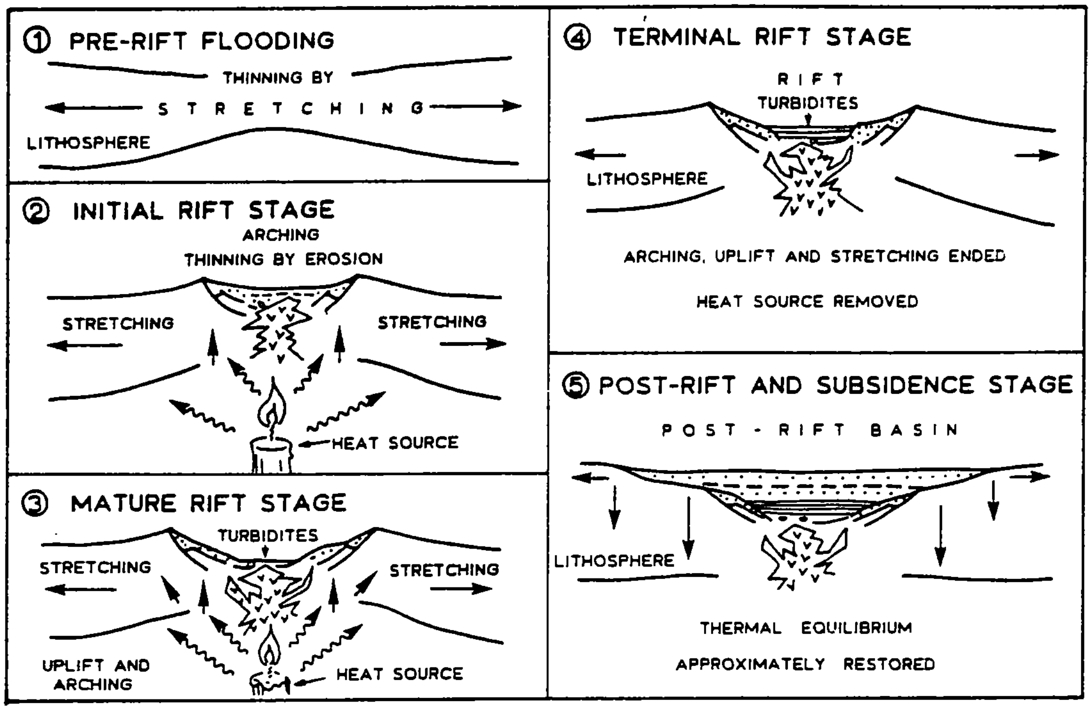


Fig. 9-8. Sketches showing suggested stages in evolution of late Cenozoic basins in onshore southern California. (1) Pre-rift-flooding stage. Thinning of lithosphere owing to plate interactions accompanied by subsidence. (2) Initial-rift stage. Arching and stretching of crust and lithosphere, accompanied by rifting along crest. Volcanic rocks (v) well up from heat source in mantle, shown diagrammatically as a candle. Coarse sediments washed in from margins of rift valley change facies rapidly to finer deposits along rift trough. (3) Mature-rift stage. If sheltered from an overwhelming influx of sediment, a deep central trough may characterize this stage. The floor of the basin may be the site of deep-sea fans and turbidites brought down submarine canyons notching the margins. (4) Terminal-rift stage. The heat source has died. Crustal stretching as the consequence of tectonic activity owing to plate interactions may continue. (5) Post-rift and subsidence stage. Owing to thermal contraction in the lithosphere, subsidence ensues inasmuch as the heat source has waned so that equilibrium is restored. Sediments accumulate above the deeply buried rift sequence and overlap onto the depressed margins of the basin. Deformation continues, but controlled by simple-shear systems, including considerable lateral stretching.

## Pre-rift-flooding Stage

Beginning about 22 my B.P. for the Los Angeles, Ventura, and San Joaquin basins, the sea transgressed across subdued but irregular topography marked by embayments and promotories. The Vaqueros Formation and its correlatives were laid down in nearshore and shelf environments. Previously, during the Oligocene, widespread continental deposition prevailed. The switch from nonmarine to marine at the beginning of the Miocene followed directly upon a eustatic sea-level rise, and presumably, also the beginning of sagging as the result of crustal stretching associated with the arrival of the East Pacific Rise and the Pacific lithospheric plate at the continental North American plate. It is, therefore, not yet known to what extent the marine flooding at future basin sites was eustatic in cause, or due to local tectonic subsidence.

A similar marine flooding affected the region to be occupied later by the Salton Trough, but about 6 or 5 my B.P. The marine Imperial-Bouse Formation was laid down at this time, but with a somewhat more northerly orientation of its seaway than the later orientation of the Salton Trough (Metzger, 1968). This incursion of the sea upon continental rocks, an epeiric-type transgression, also followed closely upon sea-level rise (Hardenbol *et al.*, 1982).

The coincidence in timing between the onset of marine flooding, worldwide plate readjustments, and eustatic sea-level rising suggests that this pre-rift flooding may not have been directly premonitory to a coming rift in western North America. It is still difficult to separate local from gobal effects. Perhaps both rearrangements of lithospheric plates and eustacy were responsible for the inception of the Early Miocene basins. Pliocene sudden deepening of the western California basins, however, apparently corresponds closely in time with the origin of the Salton Trough and basins within the Gulf of California, so that there is probably a common, fundamental origin in this case. The first manifestation of a future rift may be subsidence, attended by marine flooding, represented in the Salton Trough by the Imperial-Bouse Formation.

## Initial-rift Stage

In the Salton Trough and the Gulf of California, stretching and subsidence were followed by arching some time after 5 my B.P. The arched flanks, characteristic of the rift stage, are still preserved along the margins as high rims. Uplifted erosion surfaces stand at one or two thousand meters above the level of the trough, and dip gently away, both east and west. The arching is viewed as the result of vertical thermal expansion of the lithosphere above a hot mantle welt, rising into a crust already tectonically extended and thinned. This is a pattern similar to that recognized for other rift systems over the world, as in the Red Sea, Dead Sea, East African Rift system, and Rio Grande rift (Falvey and Middleton, 1981; Palmason, 1982).

As the arch grew, widened, and stretched, the crestal region, in time, subsided. The rift overlies hot mantle diapirs and domes, and thermal gradients and heat flow are high. Sediments washed into the trough from steep margins, with local provenances, so that coarse debris prevails. Only if rivers find gaps in the marginal ramparts is debris able to enter the trough from great distances. Stretching in this tectonothermal regime predominates, so that the active sedimentation surface within the trough subsides quickly, and the present one in the Salton Sea region lies below sea level.

In the rift sequence, strata deposited during the rifting phase are either marine or nonmarine and have rapid facies changes, from coarse debris at the rift margins to fine-grained deposits within the deeper parts of the trough. At times, these fine sediments are centered within the trough; at other times and places, they hug one of the steep walls because they have been carried across the trough from uplifted sources on the opposite side. At the head of the Gulf of California, for example, evaporites accumulate from time to time within the Laguna Salada in Mexico, south of El Centro (Fig. 9-1). This long and narrow bajada lies at the foot of the steep western scarp in northern Baja California, in an isolated area so that standing water can accumulate and eventually evaporate. The rift setting is, therefore, one where thick evaporites as well as clastic sediments may be deposited.

Fine material beneath the Imperial Valley has largely come from the ancestral Colorado River, and includes much carbonate debris eroded from the rocks of the Colorado Plateau (Muffler and White, 1969). In view of the near absence of carbonate source rocks in the region marginal to the Gulf, this carbonate debris fits in nicely with the concept of distant transport by the Colorado River. Today, however, in view of the many dams along the Colorado River, no sediment and almost no water reach the Gulf of California. The water coming down the river now flows into irrigation systems or through the Los Angeles megalopolis and out to the Pacific Ocean through sewage outfalls.

## Mature-rift Stage

The Gulf of California along its central parts has widened to the point where basaltic oceanic crust is being manufactured at spreading centers (Lonsdale and Lawver, 1980; Lonsdale, 1985). At the north within the Salton Trough, however, the margins are close together, and widening has not progressed to the extent that sea-floor-spreading mechanisms have brought basaltic material to the surface. Moreover, voluminous sedimentation has nearly overwhelmed tectonic effects. Farther southeast, however, deep pull-apart basins occur along the floor of the gulf, and are relatively sheltered from sediments coming from the margins. The deep floors are the sites of turbidites arriving from the mouths of nearby submarine canyons. A similar style is visualized for the Rincon and Repetto stages of the Los Angeles and Ventura basins, that is, tectonic deepening has exceeded sediment supply.

The widening of a rift requires that sediments first deposited in the narrow trough have an areal extent limited to a long, narrow, and irregular band. Successive beds laid down on top as widening continues overlap older beds and have broader and broader extent. Beds documenting the initial subsidence are deeply buried and overlapped, and do not crop out around the rift margins. In the Salton Trough, they are pictured as so deeply buried and so subject to later metamorphism and hydrothermal alteration that their character has been grossly modified. An obvious but significant corollary of this reconstruction is that beds laid down when the basin was small cannot be everywhere at depth or near the surface when the growing basin has enlarged (Crowell, 1974b; Crowell and Baca, 1979). Another corollary is that there is no true basement at depth, that is, no true floor of older rocks upon which the beds are deposited. Beneath the central areas, sediments and volcanic rocks are intermixed and of the same age.

At some breadth in the process of basin widening, sediment no longer washes all the way across the rift, but forms prisms at either side. This stage now has



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been arrived at in the large basin at the head of the Gulf of California offshore from Guaymas in Mexico (Fig. 9-1) (Lonsdale, 1985). In the Salton Trough, however. the sedimentation surface is bolson-like. Conceptually, I picture the stages during widening as moving from the tectonostratigraphic style prevailing in the region near the U.S.-Mexican border to one farther south, where isolated deep-water basins dominate. As widening continues and sediment volumes diminish, two largely independent prisms of sediment reaching out from the two margins begin to characterize the depositional sites. With continued sea-floor spreading, two passive margins evolve, and if the movement picture continues, a new ocean is born.

Perhaps, during the Miocene in southern California, similar rift situations prevailed. Perhaps, a hot mantle ridge moved eastward with respect to the crust of California so that rifting near the coast died shortly after it began. Rift basins failed to enlarge and interconnect to make a new ocean. These basins became western orphans.

## Post-rift and Subsidence Stage

The caprices of plate interactions and thermotectonic driving forces deep within the earth may interrupt the rifting processes. With heat sources no longer concentrated beneath rift basins, cooling of the lithosphere begins. Contraction sets in and subsidence of the surface ensures. Erosion has thinned the rift margins, along with thermotectonic stretching, and the lithospheric profile has been necked and attenuated. As a consequence, the sea transgresses across the former margins, and as subsidence continues, thick stacks of sediment are laid down above the former rift axis. Subsidence may be more rapid than sedimentation if source areas are low and at a distance, and fail to provide debris in sufficient quantities to keep the basin filled.

Such a sequence is tentatively proposed to explain the histories of the Los Angeles, Ventura, and southern San Joaquin basins. These basins are pictured as having formed as irregular pull-apart basins at a time of irregular rifting, but soon thereafter, the rifting ceased. The heat source at depth disappeared. Mobility continued along the continental margin and within the simple-shear system of the San Andreas transform boundary so that deformation went on during stratal deposition. Inasmuch as subsidence affected a wider region than the initial rift, however, the strata spread widely and overlapped basin margins with time.

During the subsidence in a slowly cooling regime, strata at appropriate depths passed through the ideal thermal "window" for the maturation of hydrocarbons (see Graham, this volume). In the three petroleum-bearing basins here under review, sand source areas for turbidites lay close at hand. These source areas, consisting largely of crystalline basement, were, in part, uplifted as "porpoise backs" within the San Andreas transform belt. A eustatic rise in sea level, and the circum-Pacific flourishing of plankton, so essential in the origin of source material for hydrocarbons, also occurred at the same time (Garrison *et al.*, 1981; Isaacs *et al.*, 1983). The remarkable oil productivity of these basins is probably due to the felicitousness of this sequence. Geologic variables came together at the right times and places to make the basins veritable geocrucibles for the generation of oil and gas.

## CONCLUDING COMMENTS

Geologic data in southern California are now sufficient so that geoscientists can begin to interrelate the main plate-tectonic events of the late Cenozoic with local tectonic and sedimentation events. We can now begin to fit plate-tectonic concepts into the geologic record and make strides toward understanding the thermotectonic reasons for California's post-Oligocene history. A next step is to erect hypotheses outlining these interrelationships, and then to search for data to test them. The data are largely in hand and only need to be looked at from the viewpoint of the crustal mobility now established for the region. Such an analytical approach will suggest where new data and special studies are required.

This brief outline of the geologic history of some California basins brings out emphatically that details of the geology are complex. Crustal mobility and sedimentation have gone on together across the whole region, but with belts and areas where, for a time, either deformation or sedimentation has dominated. Cross sections are bound to get more complicated at depth, inasmuch as older beds have been subject to more deformation than younger. Geologists must abandon simplicity as a main guiding principle, and expect complexity instead. Each new bit of information, such as that obtained from a new drill hole or a new seismic line, will help in elucidating the history, but it will also add complexity to the cross section already drawn. No longer does the Principle of Simplicity, so aptly exploited in physics, for example, apply unqualified to our task. We must substitute the Principle of Complexity: in historical or configurational science, new details add complications.

In contrast to this pessimistic view, regional studies attempting to synthesize plate-tectonic regimes, eustatic sea-level changes, and climate changes (both atmospheric and oceanic) with the California geologic record may lead us toward some guiding concepts. Some order is shining through and some guiding notions are coming to light. We need now to integrate all types of investigations in order to meld the dicepherable record near the surface with understanding of deep thermotectonic events.

## ACKNOWLEDGMENTS

Intermittently over the years, since my undergraduate summer field course in 1938, I've been trying to learn about California geology. The sources of many facts, conceptions, and misconceptions are, therefore, lost in my memory. To a long series of colleagues and students with whom I have struggled to understand the geologic history of bits and pieces, I extend my thanks. Much of my research in California has been partially supported from time to time by grants from the University of California (Los Angeles and Santa Barbara campuses), the U.S.

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