THE SAN ANDREAS TRANSFORM BELT THROUGH TIME

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INTRODUCTION

The San Andreas fault system, as a continuous series of main faults and splays, has a right slip of about 330 km that began in early Miocene time about 24 Ma ago (Crowell, 1979, Stanley, 1987). This magnitude of slip and date of beginning of displacement are largely based on determining the age of strata and volcanic rocks in western California that show the maximum right slip and where, as well, all older rocks show the same displacement. The most convincing offset correlations are Miocene shorelines, facies changes, and bathymetric interpretations by Addicott (1968), Miocene volcanic centers by Matthews (1976), facies correlations by Huffman (1972), basement-rock characteristics by Crowell (1960; 1968), and Miocene facies by Stanley (1987).

To determine the maximum displacement, geologic features that correlate must be identified on the two offset walls of the fault. These statements involve concepts and caveats that require discussion. The slip on any fault is defined as the vector magnitude, lying in the fault surface, of two points that were adjacent before the faulting and are now displaced so that each of the two points is identified in the two walls. The only practical *points* are *piercing points* where *geological lines* meet the fault surface, in much the same way as one visualizes an arrow piercing a target. Our task in regional and structural geology is to idealize geological features as lines (either straight or crooked) and to locate where these lines are cut by the fault. In addition, the position and elevation of the piercing points so identified need to be known. Some examples of geological lines within pre-faulting blocks are pinch-out lines, isopachous lines, truncation lines where steeply dipping features meet overlying unconformities, intersecting dikes, isotopic and geochemical isopleths, and many others.

It may be difficult to recognize offset lines and to be sure that the offset counterparts were segments of the same line before displacement. This is particularly difficult where displacements are huge and measurable in several tens or hundreds of kilometers. Under such circumstances, the geologist establishing the correlation needs to have a detailed knowledge of the two distant areas and of the region in between. It is largely for this reason that the discovery of great strike slip on California's faults, and on major strike-slip faults elsewhere over the world, has come so late in the development of geology. The recognition that the San Andreas fault had right slip of about 300 km was not possible until much of western California had been mapped by Dibblee, and then Hill and Dibblee (1953) were able to advance their hypothesis. In southern California, a region astride the San Andreas and San Gabriel faults, about 50 km wide and well over 300 km long had to be reasonably well known, with parts much better known, before similar displacements could be documented (Crowell, 1960, 1962).

In addition, true correlatable lines and their piercing points are not always discoverable. The dispersed geologic record is too piecemeal and fragmented, some parts are concealed by younger deposits, and some of the needed record has been eroded away. Instead, displacement may need to be established by finding domains where the complex of rocks and their recorded history is deemed close to unique. Most of the great displacements on faults of the San Andreas system are advocated on the basis of such an approach. For example, the rocks of three regions in southern California are displaced on the San Andreas - San Gabriel faults: The Tejon block on the northwest is interpreted as displaced from the Soledad block which in turn is displaced from the Orocopia block farther to the southeast (FIG. 8).

Another geometric and geologic difficulty faces geologists working with great strike-slip faults. This involves the concept of *regional trace slip*. Strata and some volcanic units are laid down subhorizontally on a regional scale. Where such flat or gently undulating beds are displaced by strike slip, the slip vector is parallel to the trace of the bedding against the fault surface. The offset counterparts of reference beds across from each other will therefore display no vertical separation or throw. Both conceptually and actually, formations can be displaced for hundreds of kilometers and yet, in crossing a major strike slip fault, the same formation will occur in both walls, and with very little vertical separation. Moreover, with regional trace slip, the vertical separation along the fault may differ in sense from place to place if the formation under consideration is slightly folded. This means that at places the reference bed on one side will first be high, and then, farther along the fault, low. Note in passing, that subsurface reference layers which are contoured on the basis of well data or seismic reflections may not reveal the fault where the vertical separation is less, or of the same magnitude, as the contour interval. Such *scissoring* along the trend of a fault is therefore the result of changes in the sense of vertical separation across a major strike slip displaying regional trace slip, and does *not* necessarily represent a change in the kinematic regime so that first one side is moved upward, and then the other.

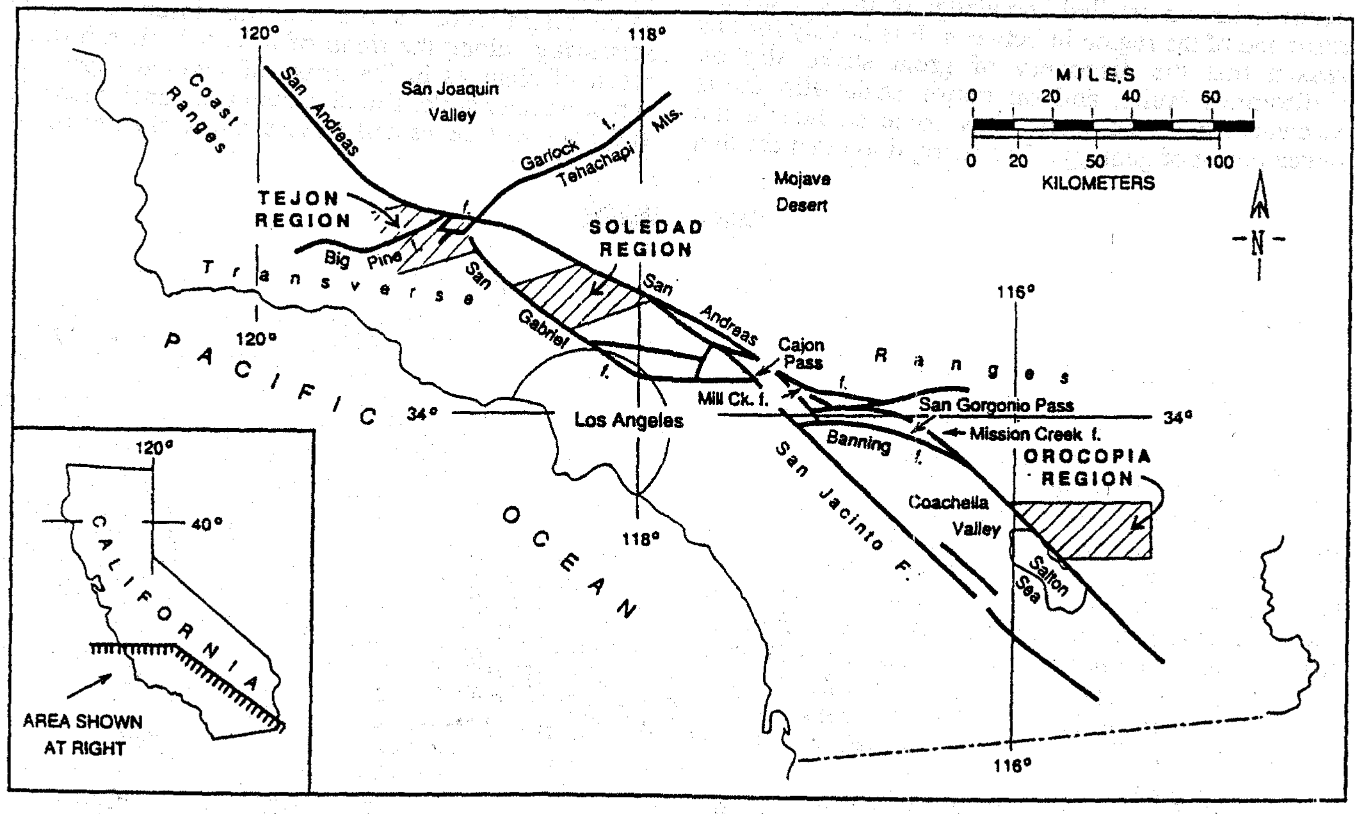

FIGURE 8 Tejon, Soledad, and Orocopia Regions in Southern California, Displaced by the San Andreas Fault. Only some the main faults are shown. From Crowell (1962).

Along the excursion route, these geometric concepts have led to vigorous controversy over the years. The Monterey Formation, of middle and late Miocene age, is widespread in California and mainly consists of siliceous shale. The San Andreas fault along several of its long reaches has juxtaposed units of the formation, so that the fault seems insignificant when crossing it, inasmuch as strata of the same lithology and biostratigraphic content occur in both walls. Many of California's large oil fields are nearby, and the Monterey Formation is an important petroleum unit. It is no wonder, therefore, that geologists, and especially petroleum geologists, were reluctant to accept the notion of major strike-slip.

Documentation of the time of origin of a major strike-slip fault is also difficult and is dependent on access to the right kind of geologic record. Where datable units are replete, as is often the case in western California, it may be possible to date the beginning of faulting rather closely using a time-displacement plot, as mentioned briefly above. Rock units containing geological lines and their piercing points *older* than a determined age will all show the same displacement. Those *younger* than this age will show successively less displacement coming up to the present through geologic time. The usefulness of finding the timing of fault onset, using such an approach, is of course dependent on having dated units that are both slightly older and slightly younger than the time of origin. At some places along the San Andreas system, such circumstances exist. At others, however, the preserved record may not straddle this critical time of fault origin. On a regional scale, however, the concept is most important. In southeastern California, for example, distinctive Proterozoic units are displaced the same amount laterally as distinctive Miocene units. This information shows only that fault displacement took place sometime during the long interval between the age of the Proterozoic basement and deposition of the Pliocene units lying above it. California geologists have therefore been searching for places where the youngest strata are preserved that show the same offset as the oldest (FIG. 6).

Two other approaches are employed in order to pinpoint the time of origin of major faults of the San Andreas system. First, with faulting at the surface, coarse sedimentary debris may be shed from a rising fault scarp, and be preserved within the datable geologic sequence. The Violin Breccia along the San Gabriel fault is such a deposit which will be examined on the field excursion. In reality, the dating of such a breccia actually dates only the timing when the fault possessed a vertical separation, and trace slip of a flat topographic surface on a pure strike-slip fault would not form a scarp. Fortunately, however, almost all of the major California faults have a slight dip-slip component and developed scarps very early in their histories.

Second, folds may grow along major strike-slip faults, following the simple-shear scheme (FIG. 4). Here the problems are to determine the age of the beginning of the folding, and to relate the folds to the beginning of strike-slip faulting. Along the western margin of the San Joaquin Valley, the interiors of several oil fields display growing folds through time, based on stratal thickness changes and unconformities (bald-headed anticlines) across the folds. The trends of these folds, both at the surface and in the subsurface, show growth through time and an increasing obliquity to the nearby San Andreas, interpreted as the result of development during simple-shear (Harding, 1976). These folds began to grow in the early mid-Miocene, but the record does not allow a more precise dating of their inception. Younger folds, including those growing at present, seem to be responding to contraction nearly at right angles to the San Andreas fault, and do not follow the simple-shear arrangement (Mount and Suppe, 1987).

DISPLACEMENT PARTITIONING

According to earth-girdling plate circuits, undertaken in order to find the total strike slip along the transform boundary between the Pacific and North American lithospheric plates, about 1500 ±120 km of total slip is required (Atwater and Molnar, 1973; Atwater, 1989). This amount of slip, based on interpretations of sea-floor magnetic anomalies, began at about 29 Ma. As described below, not more than 330 km of post-29 Ma slip can be recognized as yet on the San Andreas fault itself. Well over 1000 km is therefore probably partitioned on other faults of the system, including hypothetical major faults such as one speculated as trending along the base of the continental slope. The strike-slip displacement on such a fault is illusive, however, mainly because relatively young sea floor is on the oceanic side, and a borderland underlain by complex geology on the continental side; therefore, there is little likelihood of finding previously existing geological lines to show offset. Attempts have been made, however, to match debris within deep-sea fans lying upon the oceanic plate with identifiable sources coming down offset submarine canyons (Hein, 1973). Although this work suggests progressive displacement through the latest spans of the Cenozoic Era, no information from this technique has divulged information as yet on the total displacement nor on the age of its initiation.

Displacement may have been partitioned on many other faults in the San Andreas transform belt. Several are conspicuous bathymetrically in the borderland, off both central and southern California. Many are prominent onshore, including important splays such as the Hayward and Calaveras faults in northern California, and the San Jacinto and Elsinore in southern California. In addition, components of strike-slip are known on many faults in the desert regions of eastern California and extending eastward into the Basin and Range Province. Some of these faults are active as shown by both geomorphic features along them and geophysical events associated with them. Others are overlapped by upper Cenozoic deposits of different ages and so have not acquired displacement since their deposition. Some of the older ones, but still younger than mid-Oligocene, have been bent and deformed and abandoned. Many years of work remain to document both the partitioning and timing of displacements on the various faults.

Before the inception of the San Andreas system of strike-slip faults, long faults probably existed within the region, and especially during times of oblique plate convergence (McLaughlin, et al., 1988; Avé Lallement and Oldow, 1988). Basement segments constituting the Salinian block and within the southern California borderland are interpreted as having been assembled by lateral movements during late Mesozoic and early Tertiary time. Some of these faults are sutures where far-travelled blocks docked against coastal blocks. These faults in several instances are suspected to have been reactivated when the San Andreas system prevailed. Thus, some of the long and straight faults of western California may have originated as sutures between far-travelled blocks, others may have come into being during oblique convergence within rocks continentally inboard from the trench, and others may have been born when the Pacific plate met the North American plate. Here we are considering those that acquired displacement as the result of transform displacement between the two plates as the only ones truly belonging to the San Andreas system. These will include those showing post-mid-Oligocene displacements even though the fault originated earlier under an entirely different tectonic regime.

Some of the older strands of the San Andreas system that will be examined or discussed on the excursion include deep displacements on the Newport-Inglewood fault (still active), faults in the Banning Pass region at the northwestern end of the Salton Trough, the San Gabriel fault (it was probably the main strand of the San Andreas system between 12 and 5 Ma and formed the margin of Ridge basin), and the Pilarcitos fault within the San Francisco Peninsula. In addition, many strands of the fault system were recently active but are not now marked by active-fault landforms. Several additional "dead" faults are required by geologic relations but are out of sight beneath alluvium or young deposits that are not ruptured.

DISPLACEMENT ALONG THE SAN ANDREAS FAULT

The recognition of many tens of kilometers of strike slip on the San Andreas fault proper came slowly in California. In 1953 Hill and Dibblee published their landmark paper suggesting that the main strand of the present system (here referred to as the San Andreas fault proper in order to distinguish it from the system of many subparallel faults) had a total displacement of as much as 560 km. Their data indicated that this displacement had taken place since Jurassic time, but since 1953 information on the splays and strands, and on the ages of rock units displaced, now indicates that the difference between 560 km and 330 km, 230 km, includes both older faulting in pre-mid-Oligocene time, and the displacement contribution of splays joining the

San Andreas fault in northern California. The principal splay is the San Gregorio-San Simeon-Hosgri system which is viewed at present as perhaps adding as much as 115 km of right slip (Graham, 1978; Page, 1981). This fault system, as well as others, have played a part in the elongation of the Salinian block.

Prior to the Hill and Dibblee paper of 1953, several geologists had written concerning major strike-slip faulting in California. Noble (1926) was the first to show major strike-slip on the fault, on the reach bordering the Mojave Desert on the south. Here distinctive Miocene conglomerate bodies were offset about 40 km. Wallace (1949) suggested large right-slip, but was unable to find tie points of older rocks to establish total slip, nor its timing. Other papers dealing with right-slip of many kilometers preceded the Hill and Dibblee paper but on faults of the system rather than on the San Andreas proper. These include that by Vickery (1925) on the Calaveras fault and by Crowell (1952) on the San Gabriel fault.

Since the mid-1950s, many studies have added to our knowledge of the displacement history of the San Andreas fault proper. In central and northern California, especially significant contributions have been made by Curtis et al. (1958), Hall (1960), Fletcher (1967), Addicott (1968), Ross (1970), Huffman (1972), Matthews (1976), Nilsen (1984), and Stanley (1987), as well as by many others who have added valuable information and interpretations on local areas. In southern California, contributions have been made on the displacement history of the San Andreas proper by Crowell (1960, 1962), Ehlig et al. (1975), and Powell (1982), although, again, many investigators have contributed vital regional data. Smith (1977) marshalled evidence to propose that a major fault strand was active during Miocene time by connecting faults through the Salinia block (Red Hill, Chimineas, San Juan, and others), to faults within the Transverse Ranges, and thence to the Clemens Well fault in the Orocopia Mountains. Crowell (1982a) has shown that the San Gabriel fault was the main strand of the system in late Miocene time and was then abandoned about 5 Ma. At that time, corresponding with the opening of the Gulf of California, reinforcement of the "big bend" of the fault, and elevation of the Transverse Ranges, the main San Andreas strand moved to its position bordering the Mojave Desert and connected highly deformed regions between Tejon and Cajon passes. The story is by no means completed, and research on how to link together major faults through time is still underway.

SUMMARY

The displacement histories on the San Andreas fault proper for northern California can be represented by a time-distance diagram such as the one prepared by Stanley (1987). During the decades ahead, such a plot will be improved and extended to the fault system as a whole. As changes in the rate of slip are documented, because the transform belt is complex, we can be sure that different faults of the system will be shown to have been active at different times. We now know that some have changed their rates of displacement through time or have been reactivated following episodes of dormancy. Moreover, recently proposed models, based in part on paleomagnetic data gathered during the past decade by Luyendyk and his colleagues, suggest that different stretches have displaced at different times as the continental margin has been subjected to simple shear (Luyendyk, et al., 1985; Kamerling and Luyendyk, 1985).

The evidence now in hand suggests that the San Andreas fault zone (properly defined, but including a few strands) has a total right slip of about 330 km, and that this slip has accumulated irregularly since the end of the Oligocene epoch. It is also clear that strike-slip faulting of major tectonic significance took place along the margin of the continent at intervals long before that time (Stewart and Crowell, in press).

THE TECTONIC HISTORY OF THE SAN ANDREAS TRANSFORM BELT

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INTRODUCTION

California has been at or near lithospheric plate boundaries during much of its decipherable geologic history, and at present is undergoing deformation along the broad belt of interaction between the Pacific and North American plates (FIG. 1). This belt of interaction constitutes the San Andreas transform belt which consists of many subparallel faults and folds, and the San Andreas fault itself is only one tectonic element within it. Rocks now exposed within the belt and along the course of the field excursion are made up of many types and ages. These include rocks as old as Proterozoic, and deformation accompanied by sedimentation, volcanism, and plutonism has taken place during this long interval since then. The San Andreas transform belt, however, originated only about 30 Ma, and many of the rocks and structures are older than this. It is essential to sort out and separate those features resulting from the evolution of the San Andreas system from those that are older.

The geology of California is therefore complex because of the progressive superposition of profound tectonic events upon one another from late Proterozoic time to the present (Dickinson, 1981; Ernst, 1981). Eastern California and western Nevada were the site of a passive continental margin from late Proterozoic to middle Triassic time when more than 15,000 m of miogeoclinal strata accumulated on the edge of a craton consisting of older basement rocks. This great prism of Cordilleran rocks was intermittently deformed on the west by the collision of plates coming in against the North American continent from Pacific Ocean regions during Phanerozoic time. The Antler Orogeny took place in Devono-Carboniferous time when a huge and complex mass impinged against the Cordilleran prism along the Roberts Mountain thrust system. Later, in Permo-Triassic time, an island-arc terrane was accreted to the continent during the Sonoma Orogeny along the Golconda thrust. The record of both the Antler and Sonoma orogenies, however, is preserved primarily in Nevada, and only fragments of this record reach as far southwest as the San Andreas fault system. Moreover, only locally along the San Andreas belt are Proterozoic, Paleozoic, and rocks identified that are older than Late Jurassic.

The structural framework of western California is dominated by the remnants of plate convergence and its products between late Jurassic and mid-Tertiary time. An evolving and intermittently changing trench-arc system prevailed during this long interval of about 140 Ma. Principal products of this long and complex series of deformations are the great batholiths of the Sierra Nevada and Peninsular Ranges, very thick sediment accumulations lying upon ophiolitic floors within forearc basins (Great Valley Sequence), melanges and disrupted parts of trenches, trench slope, outer-arc ridges, and accretionary prisms (Franciscan Complex). Blocks within this vast subduction complex include blueschists which record high pressure metamorphism deep within a subduction zone where temperatures were far below normal for those depths. These blocks and tectonic units have since reached the surface tectonically. Other blocks may have been scraped off of subducting oceanic plates far from their resting place today. Some are viewed as coming from seamounts and oceanic plateaus within ancient Pacific oceans. Others may have been cut from the margin of Central America and then carried northwestward by ancient transform displacements (Crowell, 1985).

In fact, much of the margin of western North America consists of tectonostratigraphic terranes that have docked against the continent and constitute regions with distinctive rocks and inferred geologic histories. At places the sutures where such exotic blocks have met the continent are identified but many of the blocks are only "suspect", and their joining sutures are not recognized. The designation of distinctive terranes, characterized by their own geologic history, and the search for sutures bordering them and their regions of origin, constitute challenges intriguing many geologists.

The San Andreas transform belt, consisting of strike-slip faults and associated folds and other structures, originated in mid-Oligocene time, following a period of tectonic adjustment to the waning and ending of subduction. This belt formed along the boundary between lithospheric plates coming in from Pacific regions and the North American plate. At the end of the Miocene epoch, the Peninsula of Baja California was sliced from western Mexico, and the Gulf of California was born. The Baja Peninsula and western California are now moving relatively northwestward along faults of the San Andreas system as the Gulf of California widens. The San Andreas transform belt proper is now about 1200 km long and 500 km wide. At places, transpression prevails within the belt so that crustal blocks are contracted; at others, transtension has resulted in deep and irregular pull-apart basins. Blocks within the splintered system have been rotated (Luyendyk et al, 1985).

Because these tectonic processes along this continental transform belt are at work today, in reviewing briefly the tectonic history of western California, it is logical to work from the present backwards in time.

THE TECTONIC SETTING AT PRESENT

Today the San Andreas transform system extends from the Salton Trough, at the head of the Gulf of California, to the Mendocino Triple Junction in northern California. Well to the southeast, off the coast of southern Mexico, the East Pacific Rise comes into the continent from the floor of the deep Pacific Ocean, and enters the Gulf of California. The gulf constitutes a divergent plate boundary. Associated convergent plate boundaries lie northwest of the Mendocino triple junction and far to the southeast off the coast of central Mexico, where oceanic crust moves beneath the North American plate. The divergent plate boundary within the Gulf of California and the San Andreas transform system provide the tie between these two convergent realms.

Upon the floor of the Gulf of California active spreading centers, here viewed as sidestepped parts of the East Pacific Rise, lie between northwest-trending transform faults. Most of these faults do not extend into continental rocks on either side of the Gulf, that is, into either mainland Mexico or Baja California. On the northwest, the divergent plate boundary narrows and forms the Salton Trough. Here the San Andreas transform system, consisting of several subparallel strike-slip faults, takes over plate movements on to the northwest (FIG. 1).

Along the San Andreas transform belt, coastal California and the adjoining Baja Peninsula move relatively toward the northwest as part of the Pacific plate. Although the San Andreas fault proper is the main transform fault in this displacement, several others (San Jacinto, Elsinore, Hayward, etc.) play an active role. Long slices between these faults - because the faults are not exactly parallel to lithospheric plate movements - are either squeezed or stretched as plate movements continue. Where squeezed, the blocks are raised to make uplands or mountains, and where stretched, they underlie lowlands or basins. The arching upward and bowing downward of these long slices, all caught in a regime of active lateral displacement, is referred to as "porpoise structure" (Crowell and Sylvester, 1979). The transform belt along the field excursion route is therefore broad and complex, and the geology reflects not only active deformation going on today, but also tectonic movements and geological events of the past.

THE GEOLOGIC HISTORY OF WESTERN CALIFORNIA

The San Andreas transform system, and the principal fault itself, originated when the Pacific Plate first nudged against the North American plate, in mid-Oligocene time. Before that impingement, plate convergence existed along the margin of the North American continent. The transform system has lengthened and broadened since mid-Oligocene time, but the regions of convergence remain today off of central Mexico on the southeast and off of northern California, Oregon, and Washington on the northwest. The history of this lengthening and broadening of the transform system through time is illustrated by means of a time (vertical coordinate) and geographic (horizontal coordinate) plot of plate tectonic events in late Cenozoic time (FIG. 6). The diagram is based on fitting together interpretations of magnetic anomalies from the sea floor with those from the geologic record on land. Because of uncertainties in the interpretation of the magnetic patterns, two plots (A and B) are shown. The Pacific plate first reached North America in the general vicinity of the Mexico-United States border about 29 Ma, long before the Gulf of California had opened. The plot shows that convergent boundaries to the northwest and southwest grew apart as the strike-slip regime lengthened, and as the Mendocino and Rivera triple junctions moved apart. The Mendocino triple junction marched steadily northwestward parallel to the coast with only slight changes in its speed. The Rivera triple junction, on the other hand, moved back and forth off the coast, and then very quickly sped far to the southeast about 13 Ma. About 12 Ma it changed directions and moved to the region off the mouth of the future Gulf of California. The rifting of continental rocks that resulted in the gulf began about 5 Ma.

Figure 6 also shows the time and place of origin of several of the Cenozoic basins that evolved within the broad transform belt. In addition, fields of time and space on the diagram depict when and where, with respect to the restored coastline, block rotations, strike-slip and rifting, and other styles of tectonics took place. With the opening of the Gulf of California beginning about 5 Ma, oblique rifting occurred within it. As the Baja Peninsula migrated northwestward, the region of the Transverse Ranges was shortened and the mountains grew. Although strike-slip dominates as the principal style of interplate displacement north of the Transverse Ranges as far as the Mendocino triple junction, upper crustal rocks are shortened in directions nearly normal to the surface trace of the present plate boundary: the San Andreas fault. The Coast Ranges are therefore characterized by folds and thrust faults nearly parallel to the transform plate boundary. These structures are now active, and the style of deformation is also shown by earthquake first motions and geodetic measurements.

The style and timing of tectonics described briefly above with reference to Figure 6 emphasizes those events younger than about 30 Ma. Older tectonic features have been overprinted by these events, but are nonetheless conspicuous in parts of the region traversed by the field excursion. Prior to the Miocene epoch, when convergent tectonics prevailed along the California margin, the Pacific oceanic floor gave way eastward to a subduction zone inclined beneath the continent. At the beginning of the Tertiary period, a diagrammatic tectonic cross-section through central California shows, from west to east, a gently flexed

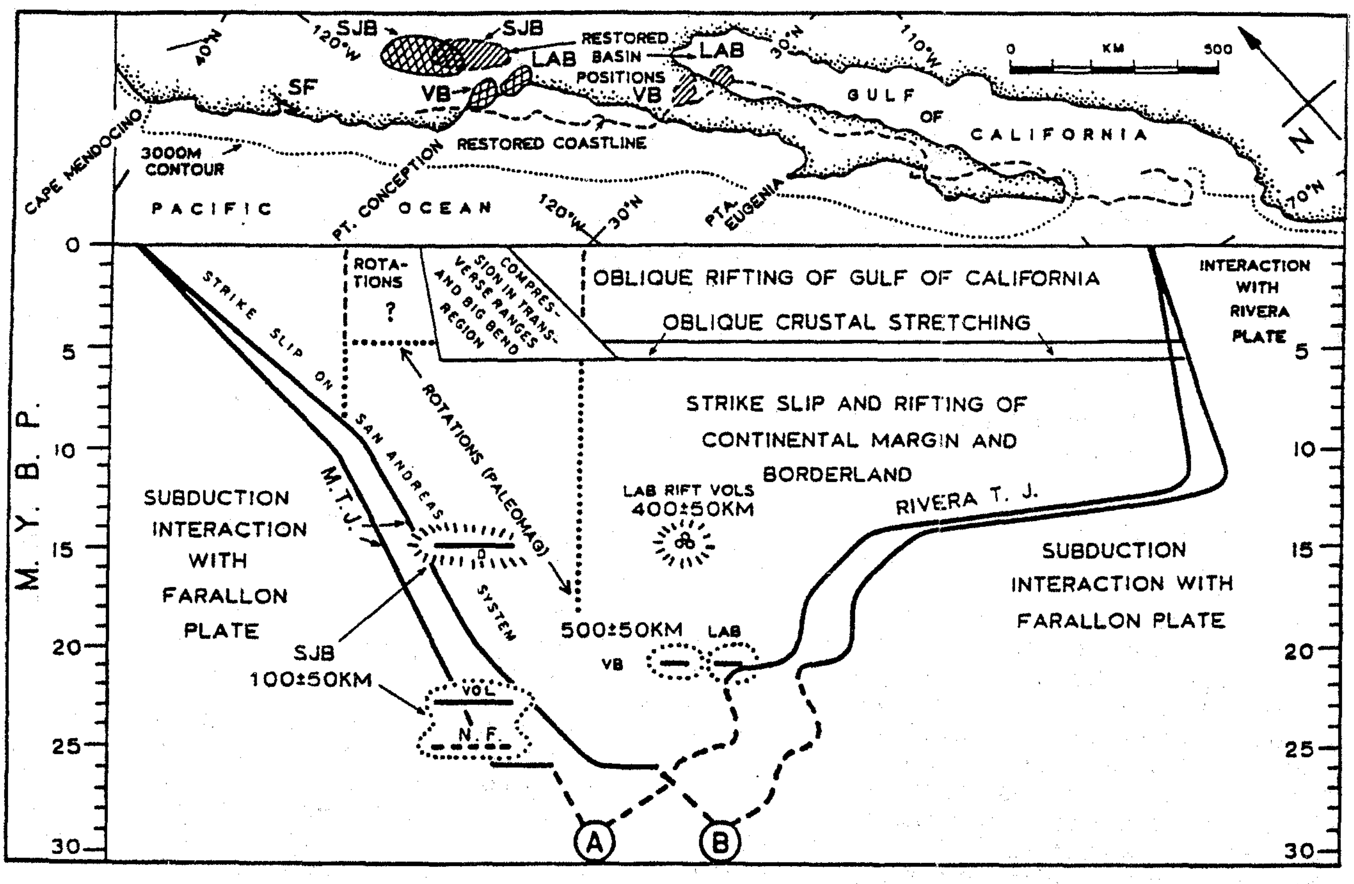

FIGURE 6 Diagram Showing Plate-boundary Regimes and Deformation in Late Cenozoic Time with respect to the California and Mexican coastlines, restored to their approximate positions about 10 Ma. The restoration is based on seafloor magnetic anomalies and derived plate-circuit reconstructions (Atwater, 1970; Atwater and Molnar, 1973; and Atwater, in Crowell, 1987a). The present shoreline is shown for approximate geologic reference. The coordinates for the diagram are geography (horizontally) and time (vertically). Two favored time-position curves of the Mendocino and Rivera Triple Junctions show the timing and possible locations for the onset of interaction between the Pacific and North American plates. The 29 Ma date of this event and the locations of the present-day triple junctions are reasonably well established. Path A suggests that this breakup occurred off what is now southern California. This initial interaction between the Pacific and North American plates was followed by tectonic stretching and subsidence, including basin formation. Only after several millions of years did the San Andreas transform fault begin to lengthen through the activity of the northward-migrating Mendocino and southward-migrating Rivera Triple Junctions. The geologic time and geographic locations lying within these paths of plate interaction imply positions within the evolving strike-slip regime at a given time. In the upper diagram, the Ventura, Los Angeles, and San Joaquin basins are shown as dotted ellipses based on data described by Crowell (1987a) and data presented by Goodman et al (in press). The origin of the San Joaquin basin may have been outside this boundary or, alternatively, the timing of this event may locate the triple junction and thus favor Path A. The approximate time of deepening for the Tejon embayment is denoted by 'D' within the dashed area and lies well within the strike-slip regime. Other symbols: SF - San Francisco; LAB - Los Angeles basin; VB - Ventura basin; SJB - San Joaquin basin; M.T.J. - Mendocino Triple Junction; N.F. - onset of normal faulting at Tejon embayment (estimated), VOL - extrusion of Tunis volcanic rocks at the Tejon embayment. From Goodman et al. (in press)

oceanic crust, a trench, an inner trench slope (with some trench-slope basins), an accretionary prism (with a steep slope shedding olistostromes on the inshore or continental side), a forearc basin (at times narrow, at times broad), a magmatic arc, and far to the east, a backarc basin (FIG. 7). In general such a cross section prevailed as far back as Late Jurassic time.

Remnants of these pre-San Andreas tectonic domains are clearly discernible today, even though this tectonic arrangement has been fragmented and blocks displaced for many tens or hundreds of kilometers by superposed strike-slip of the San Andreas system. Blocks between major faults have been rotated. Others have been stretched to form the floors of deep basins, and still others squeezed and uplifted and as a result deeply eroded. The San Andreas fault at the northwestern end of the Salton Trough, for example, cuts through the deeply eroded foundation of the Cretaceous magmatic arc, so that granitic rocks now predominate. Parts of the old forearc basin remain in the topography today as the broad Great Valley of California, and forearc strata of Paleogene and upper Mesozoic age are preserved beneath it and around its margins. The Franciscan terranes in the Coast Ranges, consisting in part of melanges with associated rocks, are now uplifted and deformed again, perhaps several

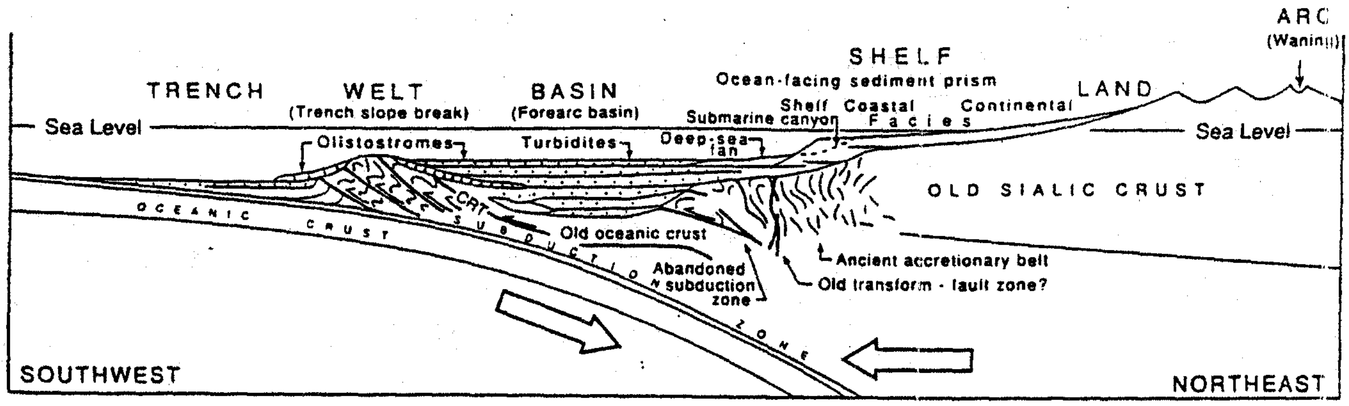

FIGURE 7 Diagrammatic Cross Section across Coastal Central and Southern California at the Beginning of Tertiary Time. CRT - Coast Range thrust; CS - Catalina Schist. From Crowell (1976, Fig. 6).

times. The terranes were originally formed within a succession of accretionary prisms and are now uplifted and exposed.

Much of the excursion route passes through country formed originally in this way. At many places within these regions, however, Neogene beds lie unconformably upon trench-arc units, and these younger beds in turn dip steeply and have been markedly folded and faulted. Clearly the older beds below have been folded and faulted also, so that some of their complexity is the consequence of these later and oft-repeated deformations. The crustal rocks of California have been subjected to many deformations through time.

The tectonic mobility is shown by interpretations of paleomagnetic and paleontological data, and by displacements on major faults such as the main strands of the San Andreas system. For example, within Mesozoic strata along the coast in central California, the remnant paleomagnetic vectors record a very low angle of inclination. This suggests to several workers that slices of terrane have been displaced several thousands of kilometers from low latitude and equatorial sites. The slices are viewed as displaced from their sites of origin and then accreted to the continent along sutures far to the north. Sea-floor spreading mechanisms associated with great transform displacements are visualized as responsible. Other geologists, however, are skeptical of movements of this magnitude because they consider several of the supposed far-travelled blocks as matching satisfactorily continental terranes that are only a few hundred rather than a few thousand kilometers away. Studies concerning the magnitude of these displacements are now underway by California geologists.

Faunal provinces mapped within Tertiary strata show significant horizontal offsets along the San Andreas fault, but these separations are not larger than those shown by the matching of offset rock units. For some Mesozoic faunas, however, the displacements are interpreted by paleontologists to be several times larger, but the displaced faunas are recovered largely from blocks isolated within melanges or from small fault slices. The rocks do indeed show evidence, at places supported by paleomagnetic data, that they have travelled far across the Pacific Ocean from seamounts or other sources before accretion to the continent.

Rocks exposed at places in western California are older than Upper Jurassic. Tracts of gneiss, schist, granulite, and other metamorphic rocks are known to include Proterozoic, Paleozoic, and pre-Upper Jurassic rocks. Some of these are clearly related to the North American craton, and have been torn from it and displaced within the San Andreas system. Others have been broken from the continent and occur as pendants and septa within the Mesozoic arc rocks. Masses of marble, quartzite, and hornfels, for example, come from miogeoclinal prisms still preserved in eastern California and adjoining states. Major structures, such as the Vincent thrust system are preserved within the crystalline basement and within Mesozoic and Tertiary strata. These document major tectonic events previous to the onset of San Andreas displacements.