NEOGENE DETACHMENT AND STRIKE-SLIP FAULTING IN THE SALTON TROUGH REGION AND THEIR GEOMETRIC AND GENETIC INTERRELATIONSHIPS

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ABSTRACT

The Salton Trough region of southern California records Neogene deformation and sedimentation related to both the classic San Andreas strike-slip system and Mesozoic compression and convergent margin magmatism. Besides these Mesozoic and late Tertiary tectonic features, an intervening deformational, sedimentological, and magmatic episode of crustal extension has profoundly affected the region. This extensional deformation is part of a much larger region of crustal extension across much of western North America, including the regions now called highly extended terranes. The Salton Trough originally opened as a half graben basin within this extensional terrane and contained multiple detachment faults within the array of domino and listric faults that offset the region west of eastern New Mexico, east of the Rio Grande Rift. This stacked array of extensional faults collectively extended the crust, offsetting Mesozoic fabrics such as the Santa Rosa Mylonite zone and the Chocolate Mountains thrust. Faults developed during this segmentation of Mesozoic features have often been mistakenly identified as faults of Mesozoic age.

Crustal attenuation and weaknesses created during regional detachment faulting appears to have localized the presence of many of the major faults within the San Andreas transform system. Strike-slip motion on these younger faults has translated the extensional terrane laterally, but has not disrupted much of the terrane except in position. The extensional terrane provides some key piercing points that can be used to help constrain motion on the San Andreas system, both in the Salton Trough and to the west in the California Continental Borderlands. The rigid beam of the Peninsular ranges appears to have acted as a boat between highly extended terranes in the current Salton Trough region and the Borderlands. Detachment faults just offshore in coastal California are thought to mimic the geometries and timing of detachment faults exposed along the margins of the Salton Trough.

INTRODUCTION

The Coachella area lies within the Salton Trough, which is a prominent basin in southern California along which two major plates of the Earth's surface slide by each other. These two plates, the North American plate and the Pacific plate move past each other along a somewhat diffuse array of faults generally termed the San Andreas fault system (Fig. 1). The North American plate, which extends from the Salton Trough to the middle of the Atlantic Ocean, is broken into a series of major ranges such as the Orocopia and Chocolate Mountains in the vicinity of the Salton Trough. These ranges are of moderate height and are separated from adjacent ranges by alluvial valleys. This area on the east side of the Salton Trough is physiographically included in the southern Basin and Range Province, which is marked by alternating basins and ranges formed by fault offsets between ranges. Regional crustal extension by detachment faulting is well developed from the eastern margin of the Salton Trough across Arizona, beneath the Colorado Plateau, and into the Rio Grande Rift of New Mexico. Most of these offsets occurred prior to the development of the modern San Andreas, although San Andreas-related faulting does occur in the southern Basin and Range province and Mojave desert as suggested by Dokka and Travis (1990) and powerfully shown by the Landers earthquakes of 1992.

The eastern edge of the Pacific plate in the area of the Salton Trough is dominated by a coherent slab of rock forming the Peninsular Ranges physiographic province. This set of mountain ranges consists of intermediate composition granitic rocks that have intruded and metamorphosed pre-existing sediments and volcanic units. The eastern edge of this province, which forms the western portion of the Salton Trough, has been offset along multiple strands of the San Andreas system, such as the Elsinore and San Jacinto faults (Fig. 1). This gives the western margin of the Salton Trough a somewhat serrated boundary from Palm Springs to Borrego Springs and on to the Mexican border. The Peninsular Ranges are a fairly high, continuous body of rock that form a strong, solid beam to the west of the structurally weak rocks of the Salton Trough. West of the Peninsular Ranges in western California are the California Continental Borderlands, where the crust is again structurally weak (Fig. 2). This area has been deformed very similar to the region east of the Peninsular Ranges batholith, so that the strong beam of the batholith sits between zones of major extensional deformation, which appear to have developed at the same time and related to the same plate tectonic causes. Localization of the San Andreas system within the earlier extensional complex appears to be directly related to the crustal anisotropy developed during Oligocene to Miocene crustal extension.

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Field Conference Guide 1996. Pacific Section A.A.P.G, GB 73,
Pacific Section S.E.P.M, Book 80, p.263-276.

OVERVIEW OF THE SALTON TROUGH

The Salton Trough area is actually the northern portion of the Gulf of California (Fig. 1), the rift basin formed by oblique strike-slip motion between the North American and Pacific plates. Motion of the Baja, California, and western California land masses away from mainland Mexico and eastern California produced the long, narrow Gulf of California (Figs. 1, 2). The Salton Trough is thus the lowland area between these two of the major plates of the Earth's surface. Infilling of the Salton Trough lowland during the development of the Salton Trough has produced a thick veneer, or frosting, of sediments filling the valley, much like filling a construction ditch dug in the street by constant infilling of sediments and rainwater. The hard sides of the ditch hold a deposit of debris that has filled it through time, recording the events of water, wind, and collapse of the sides of the ditch. Original formation of the ditch and its subsequent deformation and ongoing sedimentation are recorded in the rocks of the Salton Trough region. By extrapolation, these relationships can be applied to formation of the entire Gulf of California region, as the work of Stock and Hodges (1988) in Baja has been applied to the entire "Gulf Extensional Province."

Sedimentary fill of the trough

The major contributor of the sediments and debris to fill this ditch and thus form the nearly flat basin floor of the Salton Trough has been the Colorado River. Sediments washing down the Colorado River were dumped into the narrow marine basin between the North American and Pacific plates and formed a large, fan-shaped delta that effectively isolated the Salton Trough region from the rest of the Gulf of California. Filling in of this Colorado River delta eventually separated the Salton Trough from the ocean and produced a region of interior drainage, which is now evident as the Salton Sea. Areas of such interior drainage have no natural outlet, much like a bathtub that is plugged. Because the water cannot leave except by evaporation, it has formed a land-locked lake and produced fine-grained sediments, or lake beds, that cover the surface of much of the Salton Trough region. The very gentle slope of the valley is thus a product of infilling of material from the adjacent rivers and evaporation of the water during the hot summer months. The sediments left by the evaporating lakes are very fine-grained muds with sands and gravels and conglomerates along their margins. The different packages of sands and gravels and conglomerates

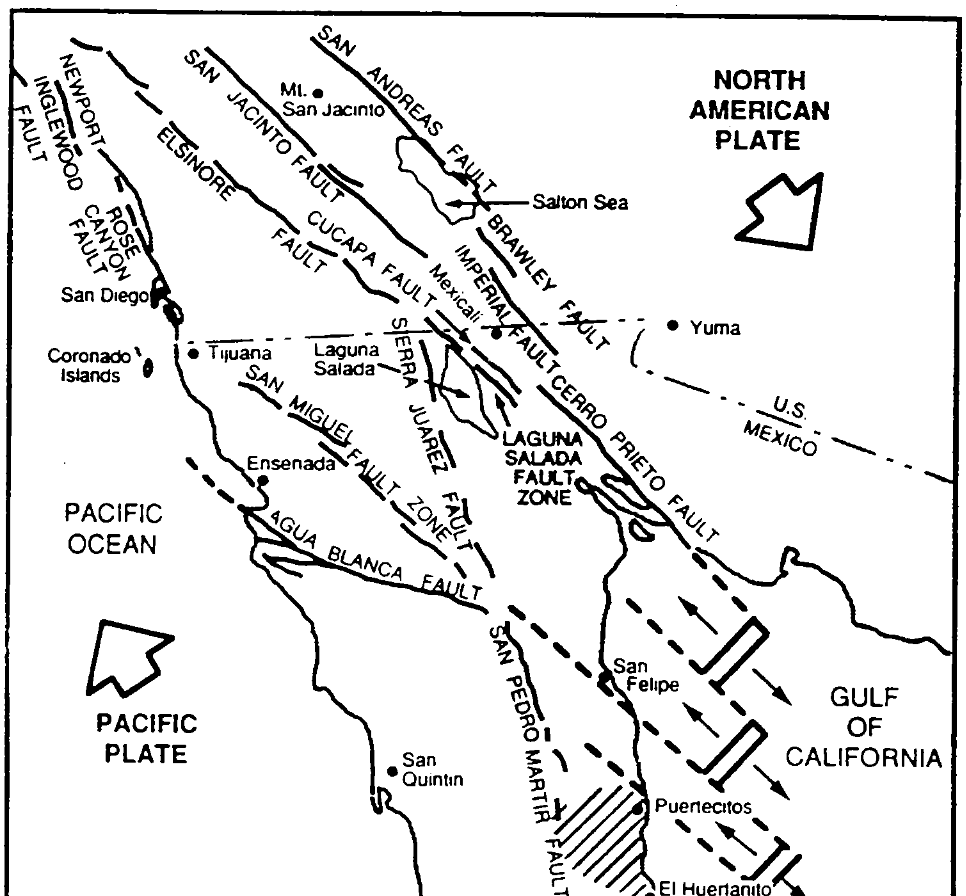

Figure 1. Location map of the Salton Trough area showing major strikes-slip faults, mostly of Pliocene age, that offset the Mesozoic plutons of Baja and California as motion is accommodated between the North American plate and Pacific plate. Region is also transected by abundant extensional faults that helped localize this mosaic of strike-slip faults. Modified from: Stock and others (1991).

(Ocotillo, Palm Springs, Canebrake Formations) and fine-grained muds (Imperial Formation and young lake beds) have produced a heterogeneous mixture of sediments that fill the Salton Trough, burying the structures and offset mountain ranges in their own debris and sediments from the Colorado River and Gulf of California.

The Colorado River delta has effectively dammed the ocean waters of the Gulf of California from the Salton Trough and the water has evaporated, leaving an area that lies below sea level. From 300 A.D. to about 1600 A.D., a lake called Lake Cahuilla extended over much of the current floor of the Salton Trough (Proctor, 1968). The old lake shores, or boundaries, of this lake are widely seen around the margins of the Salton Trough as a bright white line, much like the rings around a dirty bathtub. This veneer covered up the underlying geology of the Salton Trough like frosting a cake covers the identity and character of the underlying cake.

Faulting beneath sedimentary veneer

The presence of this frosting of lake sediments is particularly important because this veneer would cover all faulting that had occurred in the area prior to about 1600 A.D. More faults exist beneath the veneer than are known from surface outcrop as reflection seismic lines in the southwestern Salton Trough demonstrate (P. Wade and R. Zimdar, work in progress). Original formation of the valley by extensional deformation is recorded at depth and on the edges of the basin, but is nearly completely buried within the Salton Trough itself. The focus of this trip will therefore be on relationships around the margins of the Salton Trough and projection of these relationships to depth beneath the trough. Stops within the mountain ranges on both sides of the Salton Trough expose structural features that are thought to continue beneath the Salton Trough and to explain both its formation and later deformation.

Deformation of the sediments that have filled the

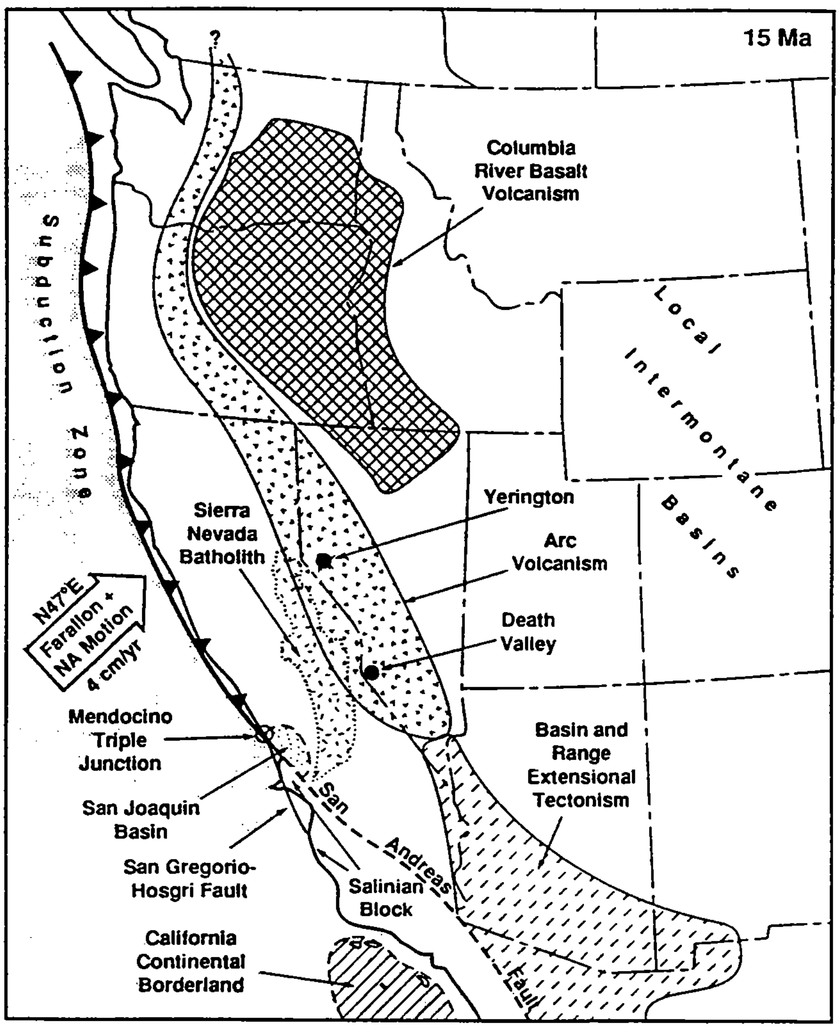

Figure 2. Paleogeography map of the western United States at about 15 Ma showing reconstructed configuration of the San Andreas fault and its relationship to areas of extensional tectonism and California Continental Borderland. The region of extension is now know to be much larger, including all the Mojave Desert and at least the southern San Joaquin Basin, as well as the entire area of arc volcanism and adjoining areas in Nevada and Utah. Modified from Dickinson (1980).

narrow region between the North American and Pacific plates has produced a series of low hills along the length of the San Andreas fault near the eastern margin of the Salton Trough. The most prominent of these low hills are the Mecca Hills, just east of the town of Mecca, and the Indio Hills, just north of the town of Indio, and the Durmid Hills east of the Salton Sea. These hills expose portions of the inside of the alluvial fill that was deposited into the Salton Trough, much like a smashed car will expose portions of the interior of the car to view. The complex folding and faulting present in these low, badlands-like hills, forms a unique landform which is world-renowned for its geologic exposures of strike-slip fault features. These classic Miocene-Pliocene San Andreas related features also sit within a framework of regional detachment faulting of Oligocene and Miocene age, which sculpted the mountain ranges and valleys that were later offset and deformed along the San Andreas system.

WESTERN SALTON TROUGH DETACHMENT SYSTEM

The Santa Rosa Mountains form the prominent mountain range on the northwest side of the Salton Trough. This name is applied to a portion of a much larger entity, the Peninsular Ranges of California and Baja, California. The Peninsular Ranges extend from Orange County to the southern tip of Baja, California (Fig. 1) and consist of batholithic rocks of intermediate composition, primarily tonalites. These granitic rocks intrude pre-existing meta-sedimentary and meta-volcanic rocks, most of which are resistant to erosion and form a fairly solid tilt block from Orange County to the tip of Baja, California. This block of rock is important in that it is a very strong beam of material composed primarily of granitic rocks that are fairly old (Mesozoic) and even older meta-sedimentary rocks of Mesozoic and Paleozoic age. These older rocks formed

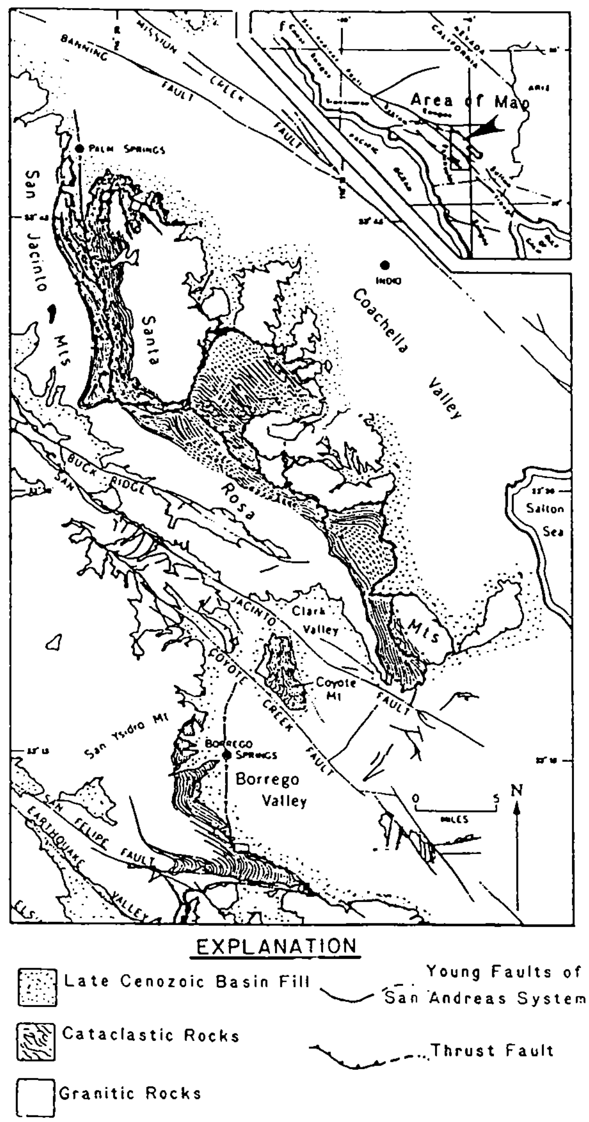

Figure 3. Classic drawing and legend of the Santa Rosa mylonite zone by Sharp (1979) and faults inferred to be thrust faults because of their association with the mylonite zone. Most of these faults are actually the detachment faults and have been offset along the San Andreas as shown by Sharp.

along the western margin of North America and include now metamorphosed sandstones (quartzites), carbonates (marbles), and shales (schist). The Santa Rosa Mountains near Palm Desert and Palm Springs display the roots of the batholith on the northeastern edge of the regional tilt block. The Deep Canyon area near Palm Desert exposes one of the deepest portions of the Peninsular Ranges known, providing a window into the geologic relationships present at depth beneath much of western California and northern Baja, California.

Mesozoic mylonitic zones

The Peninsular Ranges form such a strong beam of rock because they are thick, cold, and fairly homogeneous. They also have relatively little weak layering in them. As a consequence, these rocks are still quite intact and resistant to deformation. Old deformational or intrusive features such as ductile shear zones and pluton boundaries can be coherently followed through the entire range (Fig. 3). The most prominent ductile shear zone of mylonitic gneiss has been extensively studied within the range by Lockwood (1961), Sharp (1969, 1979), George and Dokka (1994), Erskine and Wenk (1985), and others. The same ductile shear zone has also been studied in the Borrego Springs area (Simpson, 1984), Yaqui Ridge (Schultejahn, 1984; Engel and Schultejahn, 1984; Stinson, 1990), and Laguna Mountains (Girty and others, 1993). This zone of ductile deformation appears to have formed in late Mesozoic time as indicated from fission-track uplift ages that record a time of rapid cooling ending in Late Cretaceous time (George and Dokka, 1994). Although soft and ductile when they formed deeper in the crust, these mylonitic gneisses form a very strong body of rock once they cooled and are in the upper crust, much like a melted piece of plastic. The plastic is soft when hot, but quite hard when cold. The boundary between the once ductile rocks and their overlying undeformed rocks has helped localize later deformation by extensional faulting, which in turn helped localize even later deformation by strike-slip faulting.

Offset on the San Andreas system

The Santa Rosa Mountains originally formed in an area in what is now northern Mexico and were transported to the north during offset on the San Andreas fault. Little brittle deformation actually affected this solid range during its history of deformation from its time of formation until the present. Offset along the San Andreas system seems to have moved the range rather passively to the north from Mexico. This passive motion is much like moving a large tree from one place to another, it can be scratched on the outside, but shows little evidence for all its motion because it is so strong. In contrast, the weaker rocks forming the Salton Trough on the east and the California Borderlands on the west are more visibly deformed because of their weaker crustal strength.

Progressive offset on the San Andreas fault and its related faults has moved the Santa Rosa Mountains from northern Mexico to their current position (Powell, 1993; Matti and Morton, 1993) As motion occurred along the faults, sediments were derived from both the high portions of the Peninsular Ranges and the Chocolate and Orocopia Mountains and dumped into the Salton Trough. These sediments record the history of offset along the faults, much like throwing debris from a moving car. The debris shows where the car has been. The alluvial rocks of the Salton Trough record the history of offset along the faults, with coarse-grained alluvial fans forming next to the faults and finer-grained sediments forming in the center of the valley.

Original formation of the Salton Trough by extensional deformation

Offset of the Santa Rosa Mountains to the north from Mexico moved the western margin of the Salton Trough relative to the eastern margin, like moving the cap of a pen relative to the pen. However, original formation of the Salton Trough basin occurred earlier by a different process, much like pulling the cap off a pen. This earlier history of extensional deformation has only been recognized for about 15 years (Wallace and English, 1982; Wallace, 1982; English, 1985; Schultejahn, 1984; Stinson, 1990; Duke, 1991; Wise, 1991; Lough, 1993) and is still commonly disregarded in many regional summaries of the geology of the region. The general process of crustal extension that appears to have formed the original Salton Trough is referred to as detachment faulting, or formation of a regional low-angle normal fault. This fault is exquisitely exposed in the Santa Rosa Mountains and in many other areas along the western Salton Trough region (Wallace, 1982; Schultejahn, 1984; Engel and Schultejahn, 1984; English, 1985; Beckett, 1988; Frost and Beckett, 1988; Stinson, 1990; Blom and others, 1988; Hughes, 1989; Duke, 1991; Wise, 1991; Siem, 1991; Frost and others, 1987, 1993, 1996; Kenline, 1993; Lough, 1993). Similar crustal extension occurred within much of the region of the southern Basin and Range Province and extended and tilted ranges (Fig. 4) all across the Colorado River and Mojave Desert regions (Pridmore and Frost, 1992).

The blocks, or mountain ranges, tilt over on faults much like a set of books tilting over on a bookshelf (Figs. 5, 6, 7). Multiple normal faults are the norm within the region, rather than a single major fault as was once thought. Tilting over of the faults just as the ranges are tilted over during progressive offset on multiple generations of normal faults (Proffett, 1977) produces the gently inclined regional normal faults called "detachment faults." The Orocopia and Chocolate Mountains on the east side of the Salton

Trough have extremely well developed detachment faults of this type that tilt both the ranges and overlying sedimentary rocks over on their side (Drobeck and others, 1986; Frost and others, 1986; Frost and Watowich, 1987; Robinson and Frost, 1989). The distinctive Orocopia Schist was brought to the surface during this deformation both in the Orocopia Mountains and Chocolate Mountains. Many fault features that were once considered Mesozoic thrust faults (Orocopia-Chocolate Mountains thrust), appear to have formed by regional extension and tilting over of the large crustal slabs present in the Chocolate Mountains and most neighboring ranges (Fig. 6).

These tilt blocks have provided windows into the Mesozoic and early Tertiary middle crust of the region that provide major insight as to the present-day composition of the crust in the region. The mica-rich Orocopia Schist is particularly weak and fails during earthquakes at fairly shallow depths (10 km, or 6 miles) beneath the present surface of California (Magistrale and Sanders, 1996). In contrast, rocks of the Peninsular Ranges will support brittle breaking by earthquakes down to depths of 15 to 20 km, thus providing a means of seismically imaging the subsurface structure and original detachment geometries of southern California.

This same extensional type of faulting tilted the Peninsular Ranges over so that the highest portion is on the easternmost, tipped portion of the block (such as Santa Rosa Mountains) and the lowest portion is on the westernmost, down-dropped portion of the block (coastal California). This is clearly shown by tilting of an old erosional surface that has produced a ramp-like increase in elevation from coastal California up to the high portion of the Peninsular Ranges on the western margin of the Salton Trough. Faulting in the coastal California region (Fattahipour, 1993; Fattahipour and Frost, 1991, 1992; Robinson and Frost, 1991) and offshore California region (Baker, 1994; Baker and Frost, 1992) records the movement of the west side of the Peninsular Ranges block. Such crustal extension allows mountain-range-size blocks to move apart, producing both basins for sediments to accumulate and topographic highs to shed these sediments.

Crustal weaknesses localizing strike-slip faulting

In addition, crustal attenuation occurs as mass is conserved (lengthening the cross section means that it must be thinned). Rise of hot, mobile material from the middle crust will produce broad regions of

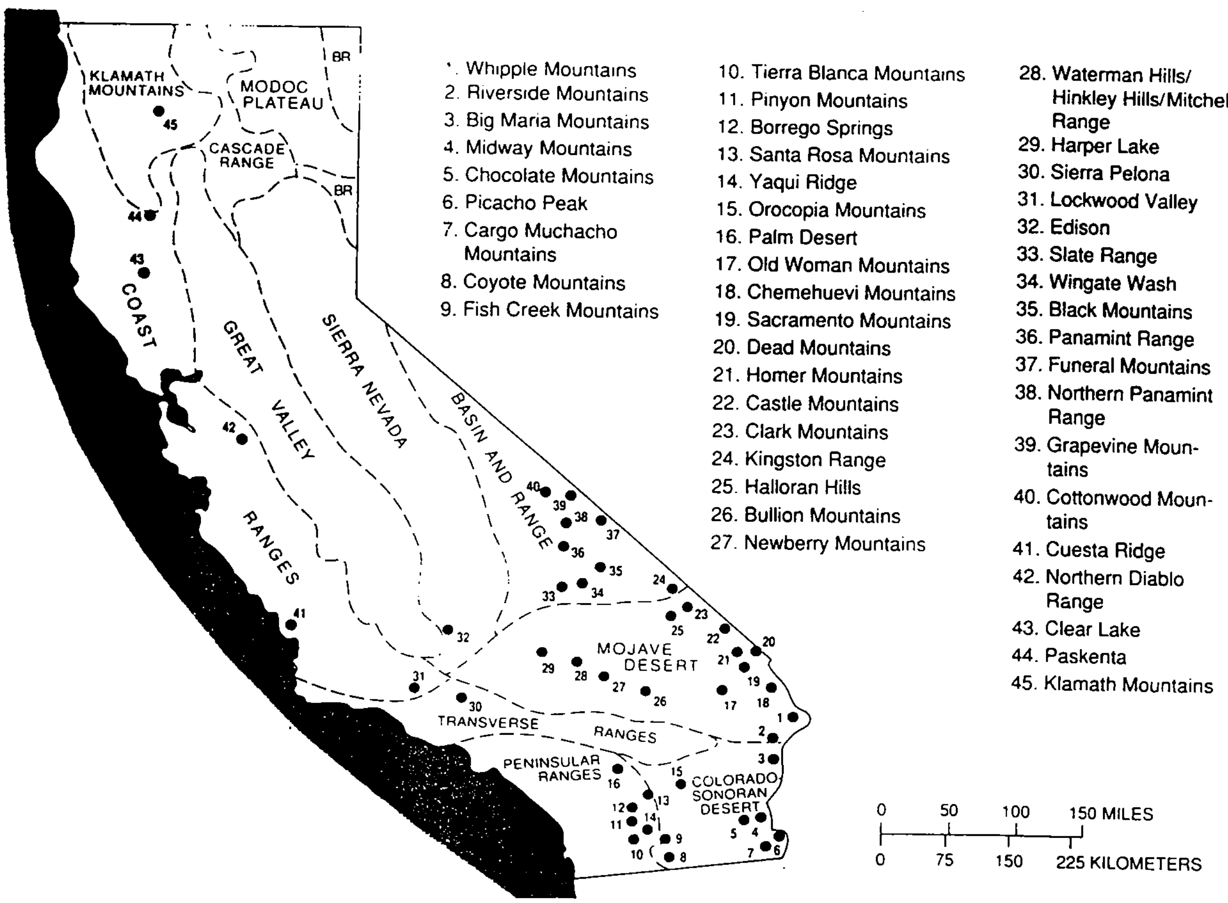

Figure 4. Location map of many of the areas known to contain detachment faults of Tertiary age within California. Areas west of the Peninsular Ranges batholith in coastal California are now also known to contain many excellent examples of this deformation. From: Pridmore and Frost (1992).

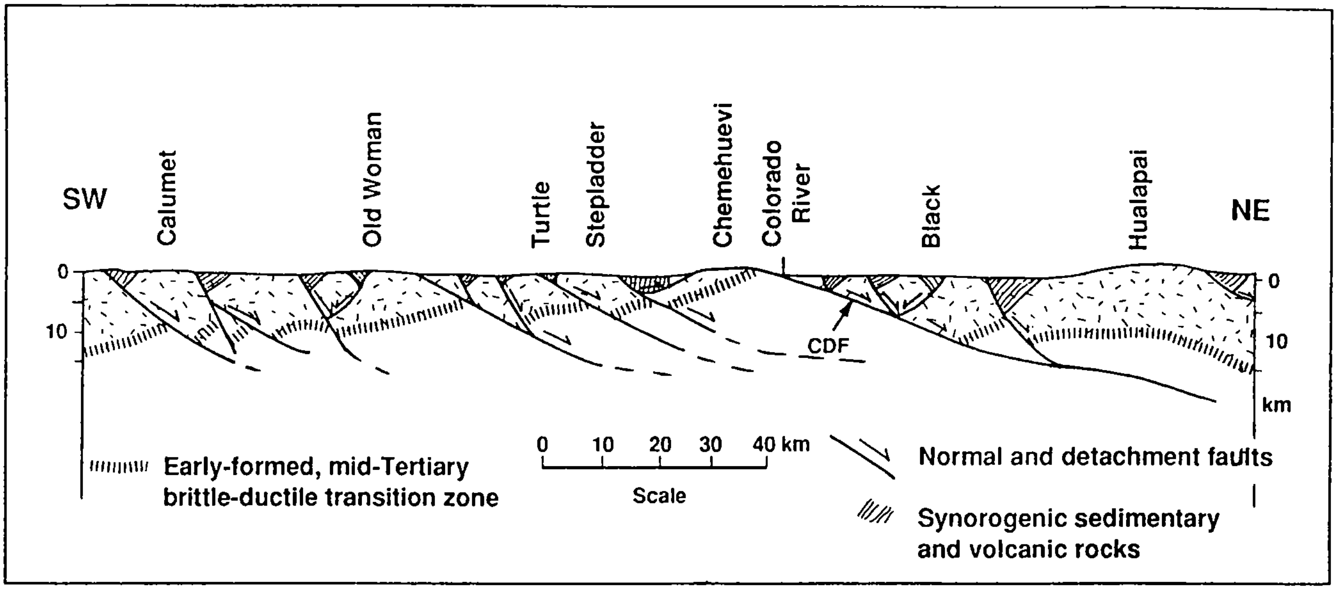

Figure 5. Regional cross section across the highly extended terrane of the Colorado River based on industry seismic lines showing the arrays of normal faults that collectively extend the crust. Where major offset occurs on the faults, once middle-crustal rocks are brought to the surface to provide a window into the middle crust. Middle-crustal ductile zone extends beneath entire region. Similar geometries extend into the Salton Trough region. From: Frost and Heidrick (1996).

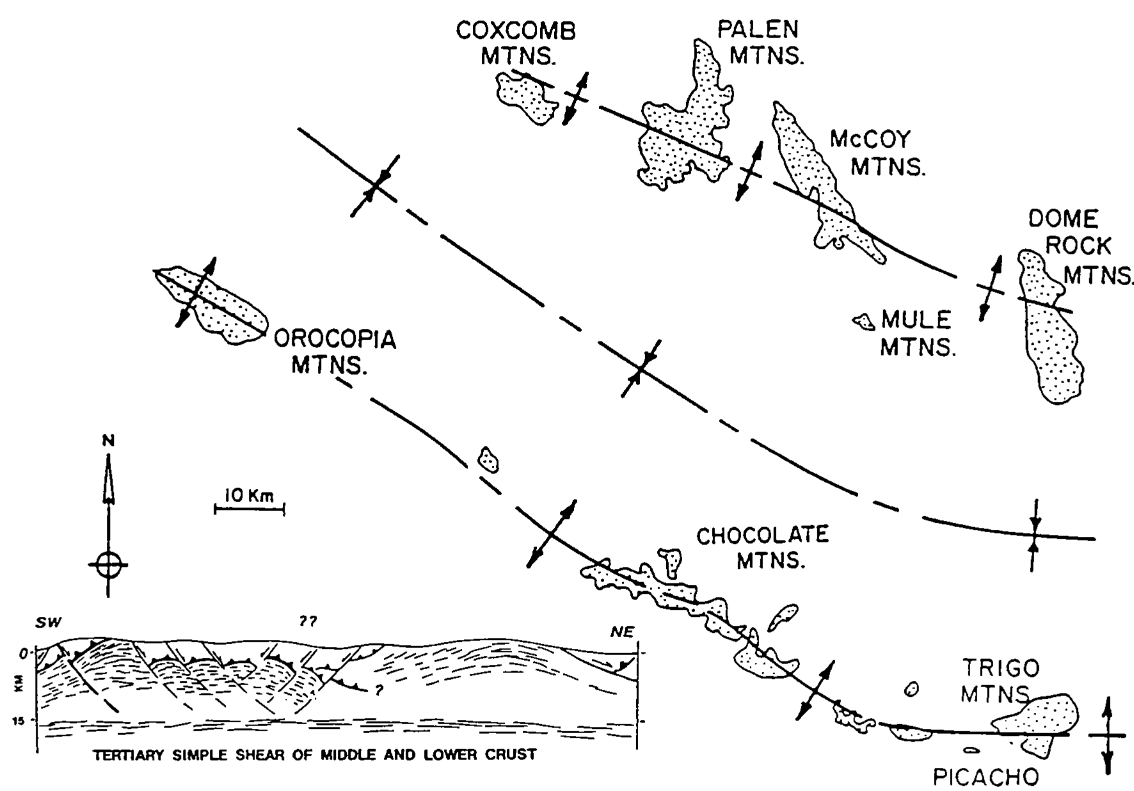

Figure 6. Regional antiforms of Mesozoic metasedimentary rocks including the Orocopia Schist. These antiforms are developed by major crustal tilting that exposes a deep footwall where major offset has occurred along the faults. Smaller-scale, mullion-like antiforms in the direction of transport bring up the antiformal highs that are exposed as individual mountain ranges. Western edge of this cross section is the San Andreas, where major offset on the western Salton Trough detachment system produced major anisotropy to help control the location of the later San Andreas transform motion. From: Frost and others (1987).

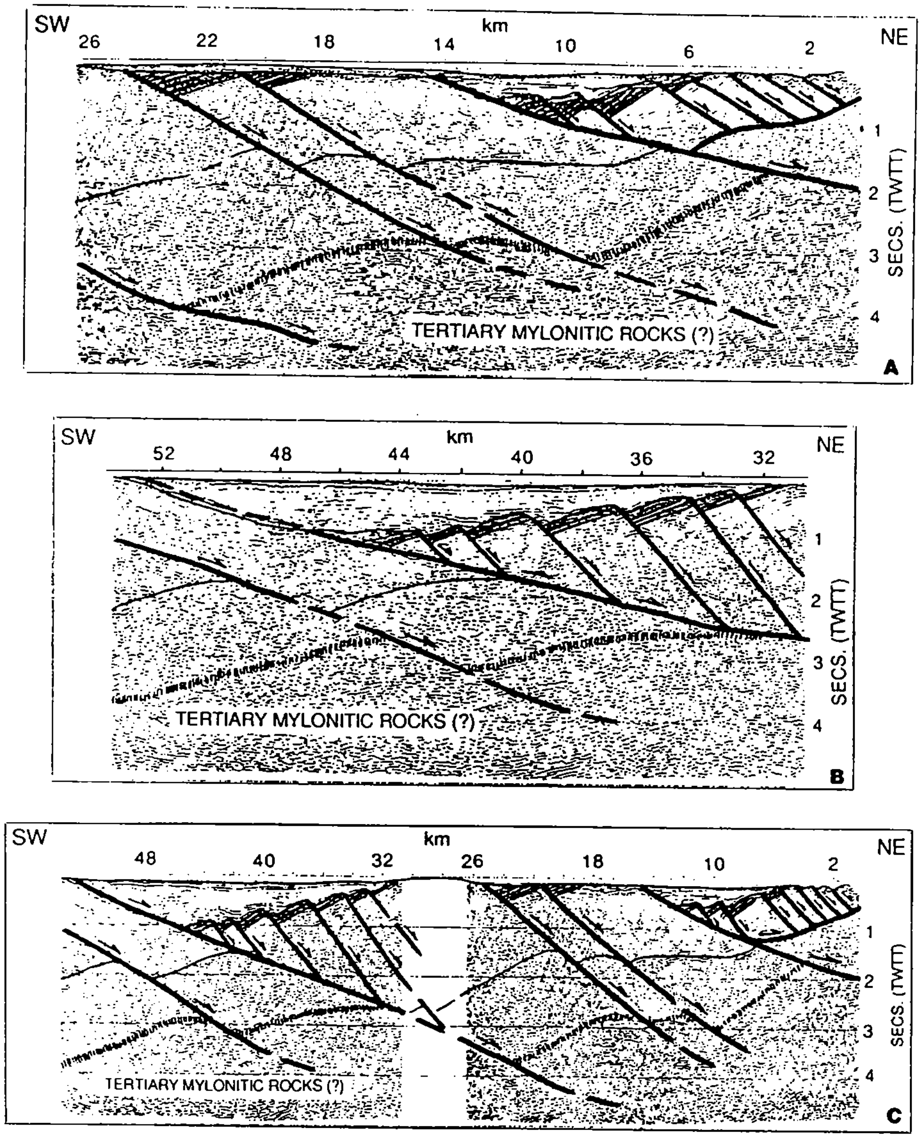

Figure 7. Reprocessed industry seismic lines between the Old Woman and Chemehuevi Mountains in the Colorado River extensional terrane showing the offset of the original brittle-ductile transition zone by detachment faults and their shape at depth. Figures A and B are blown up portions of the same section shown as an approximate depth section in section C. Offset of early-formed Chemehuevi detachment fault (now west-dipping in the upper right-hand corner of A and C is accomplished along younger, listric fault that produces hangingwall rollover of the first fault. This produces the "core-complex", doubly plunging, antiformal shape of the range to the east, the Chemehuevi Mountains. Most ranges in the Salton Trough region are not rolled over, but are like the detachment fault beginning at the top left (Old Woman detachment), which continues to middle crustal depths and is assimilated by motion within the zone of ductile creep. This is thought to be a very similar geometry to that in the Salton Trough, where the western Salton Trough detachment fault extends fairly simply to depth. The basin above the detachment in this figure is Ward Valley, where low-level nuclear waste will be placed. Detachment faults in the Salton Trough area are actually much better exposed over much greater structural distances than those in the Ward Valley area, perhaps helping to understand the geometry of a fault with major societal impact. From: Okaya and Frost (1986) and Frost and Heidrick (1996).

weakness (Figs. 7, 8), which will form weak zones for later deformation. Formation of such a region of middle-crustal weakness is thought to have localized the actual course of the San Andreas, so that the major detachment fault occurs west of the San Andreas in a system with east-dipping detachment structures. This is what is observed as the Santa Rosa Mountains detachment fault dips toward the San Andreas and tilts gently beneath the Salton Trough. This fault is interpreted to extend to the nearly vertical San Andreas fault, where it would be truncated. The three-dimensional form of this earlier extensional fault may provide powerful keys (piercing points) for more accurately matching from one side of the original San Andreas to the other, thus providing tighter constraints on the movement history of the San Andreas fault system.

Three-dimensional form of detachment faults

One aspect of the geometry of the mid-Tertiary detachment fault that is particularly important is the wave-form of the fault (Fig. 9). Rather than being a planar fault, the detachment fault has a wave-form making highs and lows much like the wave-form of a plastic garden roof. Such a wave-form appears to be a simple consequence of how rocks break in three-dimensional strain, as is commonly seen in how sidewalks break in wavy cracks. Offset along these highs and lows, or antiforms and synforms, produces highs and lows in the rocks overlying the fault as well as in the fault (Fig. 6). Motion of the hangingwall is parallel to the antiforms and synforms of the footwall, making these wave-form structures much like large-scale mullion structures. The amplitude-wavelength relationships of the major detachment surfaces provides one of the major keys to mapping the detachment faults and tracing the path of fluids that have risen along the detachment fault. One of the best known three-dimensional exposures of detachment faults in the Buckskin Mountains of Arizona has been drilled to discern the shape of the synform between two major detachment faults (Fig. 10), and demonstrates a general pattern for the form of the detachment faults throughout the detachment terrane. This pattern is of enormous assistance in discovering the locations of the faults and recognizing such extensional terranes from topography and gravity contours.

Seismic profiles in the detachment terrane of the Colorado River area provide insight into the subsurface, three-dimensional geometry of detachment faults in general. Faults appear to descend to middle-crustal depths and merge with, or shallow into, a middle-crustal zone of ductile flow. This middle-crustal layer of ductility beneath the brittle-ductile transition zone appears to be several kilometers thick and facilitates the motion of the upper crust above a more fluid middle crust. Compositional changes to more mafic material produces a stronger lower crust, producing a crustal structure much like two pieces of hard crust with jelly between them. Tilting of the upper piece of crust above the middle crust occurs during earthquakes, which rupture into the middle crust because of the rapid strain rate of the faulting during a seismic event. Slower strain rate creep occurs in the middle crust between earthquakes and is tilted upward to its eventual exposure at the surface by these multiple seismic events. Middle-crustal ductile fabrics are thus refrigerated, or frozen in, and move up into the upper crust. Mobile middle crust moves into the space, thus forming a broad wave-form of warm, more ductile crust beneath portions of the extended crust (Figs. 7, 8). This anisotropy in the middle crust is thought to bear a profound control on the localization of later, crustal-scale strike-slip faulting.

In three-dimensions, the offset of the individual ranges from each other produces broad antiformal tilt structures like those described in the following paper

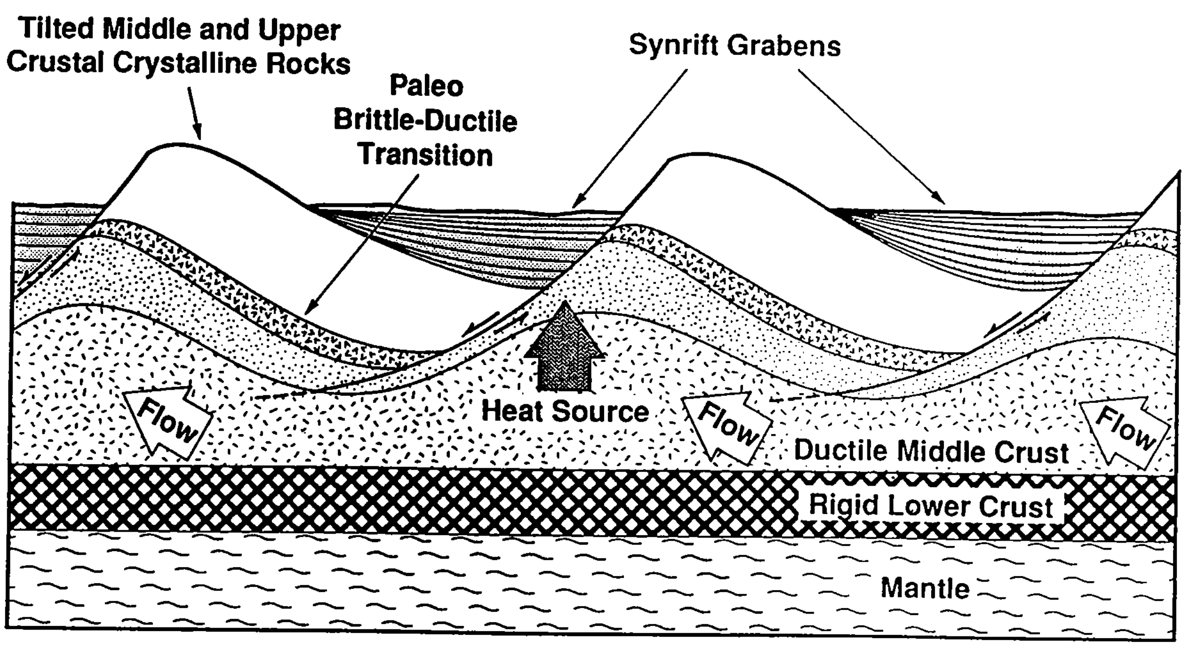

Figure 8. Drawing of a Cray computer model by Lisa Heizer (unpub. work) of the middle crustal flow of material beneath titling fault blocks developed during extension. Fairly rigid lower crust is composed of more mafic materials than middle and upper crust and is therefore much stronger. Middle crustal ductile flow produces large, pillow-like antiforms of ductile material in the middle crust. This changes heat production with basins, but also produces major crustal anisotropies that help localize later faulting along strike-slip systems. Strike-slip faults are not localized along detachment faults, but along these zones of middle crustal weakness. Detachment faults, then, are often exposed near strike-slip faults as seen in the Salton Trough.

on the Orocopia Mountains (Robinson and Frost, this volume). In the direction of tectonic transport, the smaller-scale antiform and synform shapes are best developed (Fig. 9) and produce a pronounced wave-form to the outcrops of the detachment faults like those along both borders of the Salton Trough and Colorado River extensional terrane.

In the southern Salton Trough area, the few industry seismic profiles that transect the valley appear to show major reflections that have this wave-form surface, but which define gently inclined faults tilted to the east. Where the upper-plate rocks are sediments juxtaposed against the lower-plate crystalline rocks, the faults appear to be well defined. Where the faults juxtapose crystalline upper-plate rocks on crystalline lower-plate rocks, which is by far the normal relationship, the faults are difficult to image. In this and other nearby detachment terranes, these faults typically stand out as the boundaries between packages of different seismic reflectivity rather than as distinct reflections where crystalline rocks are juxtaposed (Okaya and Frost, 1986; Frost and Okaya, 1986).

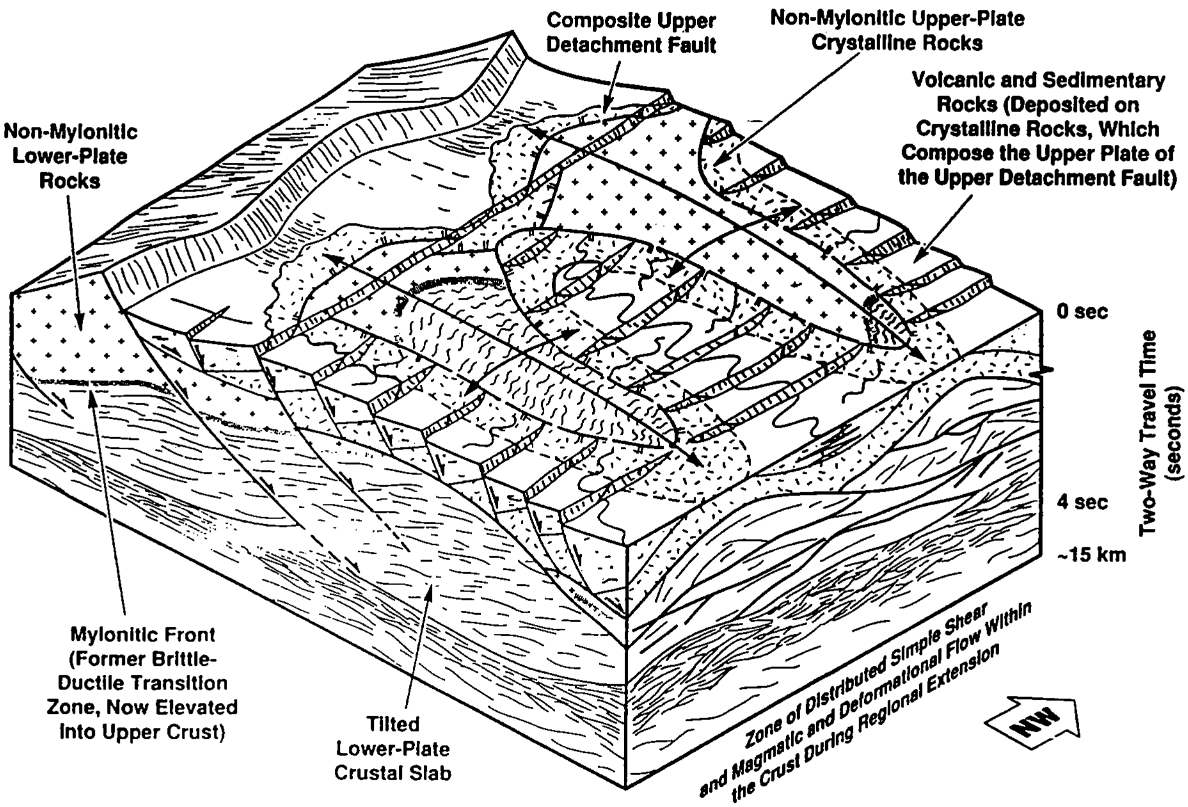

Figure 9. Drawing of a highly extended detachment system showing three-dimensional character of faults. major fault on the left side of this drawing has moderate dip and extends into the middle crust, very similar to the western Salton Trough detachment system. Antiform-synform shape of this fault is very typical of most detachment faults. Where major offset and especially offset involving two or three generations of faults (model of Proffett, 1977), these antiforms and synforms lay over on their sides, developing antiformal-synformal ranges elongate in the direction of transport. Offset of early-formed faults by later faults of listric character produces hangingwall rollover of the first faults.

Three-dimensional character of both extended middle crust and upper crust is well displayed in this diagram. Upper-crustal fault blocks are offset perpendicular to the direction of transport. Lower-plate faults blocks are similarly offset from each other. Each hangingwall-footwall identification is for a specific fault only, since many areas are hangingwall to one fault and footwall to the adjacent one. Sedimentation is strongly controlled by the shape of the faults, half grabens, and rising antiforms. Cross-cutting relationships perpendicular to the direction of tectonic transport are pronounced and produce a strong anisotropy in the crust that is visible by several geophysical techniques.

Major tilting of middle crust exposes once middle-crustal rocks to the surface in highly extended terranes. Such offset moves rocks out of the ductile regime into a higher-crustal, brittle regime. Orocopia and Chocolate Mountains are excellent examples of this ductile to brittle transition within a single deformational phase lasting for several millions of years. Similar tilting has occurred in the California Continental Borderland and along coastal California (Palos Verdes Peninsula especially). From: Frost and Heidrick (1996).

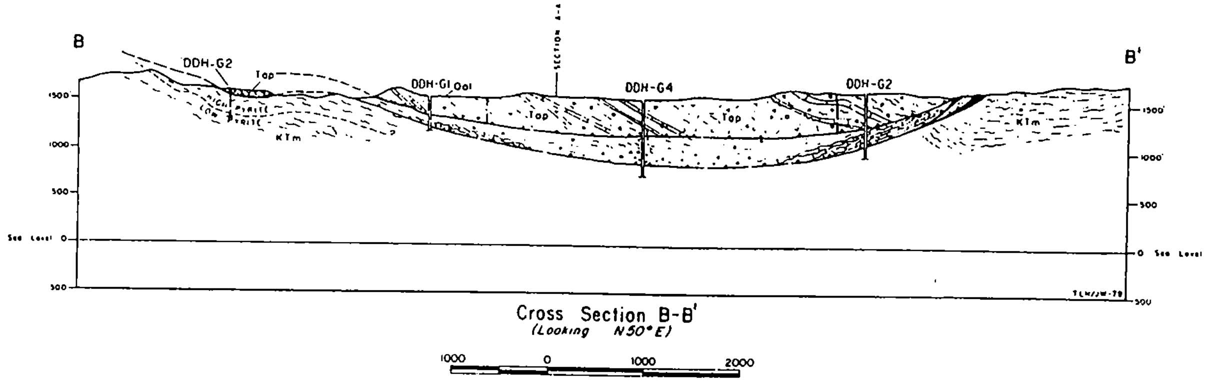

Figure 10. Classic cross section through synform within the Colorado River extensional terrane whose geometry is well known from surface mapping and drill holes through the fault block. Similar shapes of the synforms are very common within the detachment terrane and provide avenues for localization of water and mineral resources in areas such as beneath the alluvial cover of the Salton Trough. From: Wilkins and Heidrick (1982).

STRIKE-SLIP FAULTING IN THE SALTON TROUGH

Prominent hills on the northern and eastern margins of the Salton Trough are composed of interbedded sandstones and shales of Miocene to Quaternary age that have been highly deformed by San Andreas-related deformation. These young sediments overlie Precambrian crystalline rocks in the core of the Mecca Hills and overlie Orocopia Schist east and south of the Mecca Hills. This strongly deformed sedimentary veneer in both the Indio and Mecca Hills provides a window into the composition of the rocks at depth below the wind-blown sands and clays of much of the Coachella Valley and Salton Trough. The sediments of the Indio and Mecca Hills record a long history of deposition and faulting associated with the Salton Trough tectonic margin. The thickness of the sediments in the center of the Coachella Valley (Sylvester and Crowell, 1989) as calculated from gravity surveys and an oil well drilled many years ago is about 3200 meters (more than 10,000 feet). Lithologies of the different stratigraphic units are well described by Sylvester and Smith (1976), Dibblee (1954), Proctor (1968), and Sylvester and Crowell (1989).

Indio to Mecca portion of the San Andreas fault

Motion along the Indio to Mecca portion of the San Andreas has clearly produced remarkable fault features such as large-scale folding and complex breaking along discrete faults (Keller and others, 1982; Keller and Pinter, 1996; Norris, 1994). These features are physical results of the motion along the San Andreas and provide an unequivocal record that the fault has been very active in this region through time. Most of the deformation that is evident substantiates this activity is the deformation within the Indio Hills, Mecca Hills, and Durmid Hills (Fig. 11). These three hills, or structural highs, expose the compressional deformation along the San Andreas and sometimes give the impression that similar deformation is occurring all along the fault, which is not true. Instead, the compressive strain exposed in these three hills is specifically related to the strike orientation of the fault, which is producing restraining bends in the major faults at these localities. Similarly, rough protrusions on wood take up the compressional force when sanding; leaving the other areas almost untouched. Sections between the restraining bends don't necessarily display the same type of deformation as that visible in the hills that protrude into the air at the restraining bend. Rather, between the restraining bends little deformation or even major extensional deformation is occurring. The Mecca Hills, in particular, are one of the most spectacular areas along the entire San Andreas in terms of young deformation. Yet the motion occurring here is because of the restraining bend nature of the fault, and is not typical of strike-slip motion as a whole.

Offset has clearly occurred in the region of Coachella and Indio and is spectacularly shown by the offset of distinctive alluvial fans that were once adjacent to the Orocopia Mountains south of Mecca (Fig. 12). Offset of these fans along the San Andreas has moved the fans to the north on the west side of the fault, clearly showing that significant motion has occurred along the fault. Similarly, reconstructing the rocks on either sides of the faults in southern California shows the magnitude of offset along faults of the San Andreas system. This motion is interpreted to have occurred during many earthquakes through several million years to collectively yield the observed amount of offset. Lateral offset on the San Andreas system is spectacular, but appears to be rather passively moving the major crustal blocks past each other. Original formation of

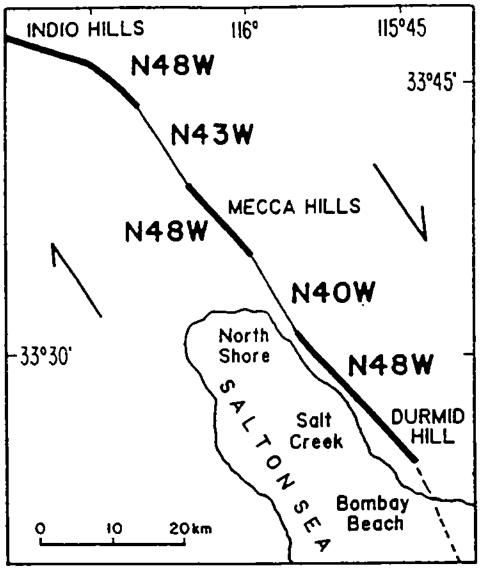

Figure 11. Restraining bend origin of the Indio-Mecca-Durmid Hills in the eastern Salton Trough. Where the strikes of the fault produce a restraining bend geometry by only a few degrees, these uplifted and strongly deformed hills are evident. Between these hills, many areas appear to have no pronounced deformation except translation along the fault. In other areas, like between the Indio and Mecca Hills, major extension has occurred. Most of the Salton Trough region has moved passively, with deformation concentrated along the restraining bends. From: Bilham and Williams (1985).

the Salton Trough region in which the San Andreas now lies appears to have occurred during the earlier time of crustal extension and detachment faulting, with these older detachment faults now moving along the San Andreas conveyor belt.

Faulting Beneath the Salton Trough

The Coachella Valley originally formed as an extensional basin between major faults, portions of which are now exposed in the Santa Rosa Mountains (western Salton Trough detachment fault of Frost and others, 1993) and in the Orocopia Mountains (Orocopia Mountains detachment system of Robinson and Frost, 1989, this volume). These faults produced a half graben basin that progressively grew as the detachment faults moved. Rocks now exposed in the coves area of La Quinta and nearby embayements moved off the high portion of the Santa Rosa Mountains and toward the east beneath the Coachella Valley. These broken granitic rocks lie above much denser and more intact rocks like those exposed in the Deep Canyon area of the Santa Rosa Mountains, where once more ductile, or migmatitic, rocks are well displayed. Offset on this detachment system is thought to have produced a major crustal weakness at middle-crustal depths that helped localize the later development of the San Andreas fault system.

The gently inclined detachment fault exposed in the Santa Rosa Mountains dips beneath the Coachella Valley, as do the crystalline rocks above and below the fault. These rocks moved apart from each other during Miocene time, ending their movement down dip at about 12 Ma, as judged from regional relationships (Blom and others, 1988; Crowell, 1989; Stinson, 1990). This fault beneath the Coachella Valley is thought to be inactive, simply recording motion prior to the development of the main strand of the San Andreas. Offset on this fault led Sharp (1972) to draw a hypothetical fault through the Coachella Valley to explain the uplift of deep-crustal rocks present in the Santa Rosa Mountains against the valley floor rocks of high-crustal origin. His observation was extremely astute and correct; it is now recognized, however, that this juxtaposition is due to motion along the western Salton Trough detachment system (Blom and others, 1988; Frost and others, 1993). Because this dotted fault has no surface exposure, no known subsurface expression or water barrier, no gravity signature, and no identified seismicity, we strongly suggest that this "fault" be abandoned from the literature. The nature of the juxtaposition for which the fault was proposed is completely explained by the Santa Rosa Mountains portion of the western Salton Trough detachment

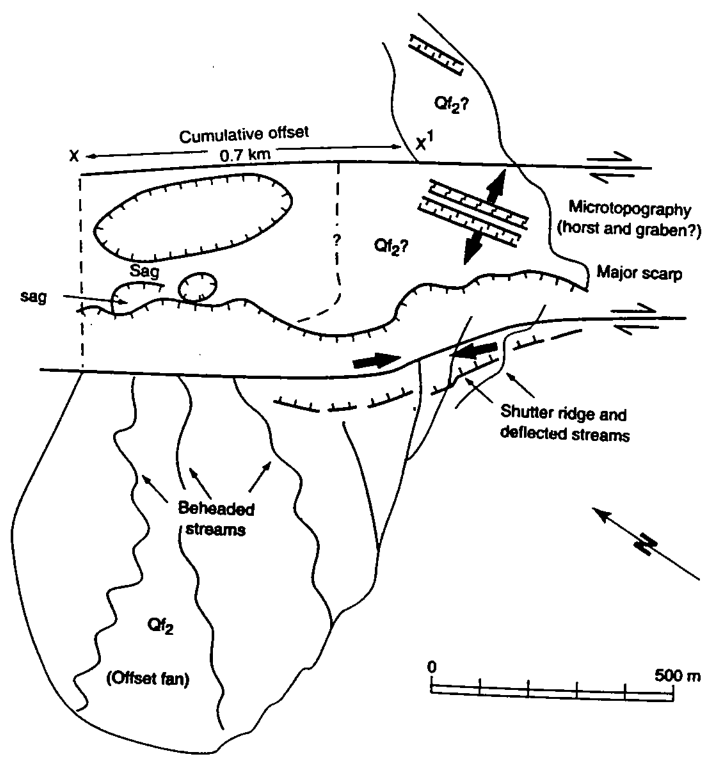

Figure 12. Offset alluvial fan in the northernmost Salton Trough area demonstrating the clear lateral transport of materials along the San Andreas. Alluvial fan is beheaded, meaning it goes back to a fault scarp, its original drainage has been offset by about 0.7 km. Lateral offset and disruption of pre-existing features is the style of deformation of the San Andreas. The extensional antiforms and synforms have similarly been offset along the San Andreas. The three-dimensional waveforms and peaks of the antiforms (like the alluvial fan), and troughs of the synforms provide powerful piercing points across the faults. From: Keller and Pinter (1996).

system (Frost and others, 1993). Realizing the distinction between Miocene detachment faulting and current faulting along the San Andreas has major implications for the people who live in the Coachella Valley. Active faulting appears to be clearly restricted to the margins of the fault blocks on the San Andreas and San Jacinto faults themselves, leaving an impressive absence of seismic events within the northern Salton Trough region.

Rocks above the detachment fault and flooring the Coachella Valley probably consist largely of the broken crystalline rocks like those in the coves near La Quinta. These fairly uniform, intermediate composition plutonic rocks (tonalites) are similar to rocks near the top of the Santa Rosa Mountains (Erskine and Wenk, 1985). This is because these rocks such as at La Quinta and beneath the Coachella Valley were transported from the central to western Santa Rosa Mountains during the Miocene extensional deformation. These rocks are fairly broken, so that they are prone to collapsing downhill during earthquakes or heavy rains, producing landslides like the Martinez Mountain landslide (Hart, 1991). The source rocks for the Martinez landslide are the highly broken crystalline rocks of the upper plate that make up Martinez Mountain. Similar broken rocks and landslides are almost surely present beneath the Coachella Valley, but have now been buried by younger valley-fill sediments. These broken rocks and landslides may exert a fundamental control on subsurface water flow and volumes. Geometric understanding of these crystalline rock aquifers and flow patterns is limited, yet these deposits represent a potentially major resource either at the base of the fine-grained valley-fill sediments, or interbedded within them to make perched aquifers.

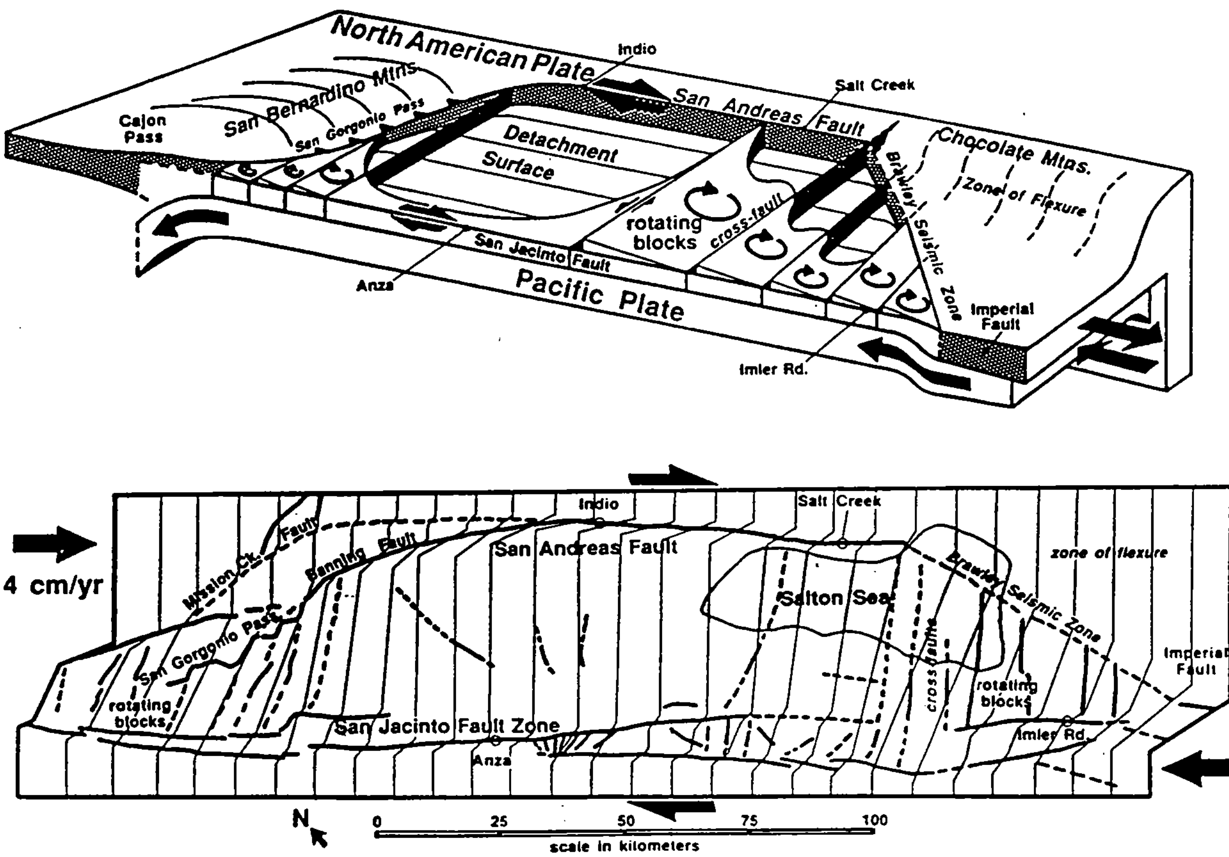

Figure 13. Map view and block diagram of the Salton Trough area showing another use of the term "detachment" for this region. This model of Gerard Bond and Ken Hudnut (e.g., Hudnut and others, 1988) highlights the decoupled character of the upper crust from the middle crust in the modern-day Salton Trough region. Microplate rotation about vertical axes is possible in this model which helps to show how the prominent cross faults in the Salton Trough and other transform regions can interrelate with the larger fault features. Modern-day seismicity is the primary control on drawing of the location of this zone of detachment, or decoupling. Where seismicity is present, the region is above or in the upper portion of the ductile (by creep) region. This anastomosing linkage seen on its side in the strike-slip system, is actually very similar to the anastomosing patterns of faults on their sides within extensional system.

Possible reactivation of the detachment fault

Reactivation of the detachment fault along the San Andreas could potentially inflict significant damage on the man-made structures of the Coachella Valley if the detachment fault moved, probably related to motion on the San Andreas system. Detailed studies of the Santa Rosa detachment fault near the foothills of Palm Desert, just south of Highway 74 indicate that no reactivation of the fault appears to have occurred during at least the time needed to form very heavy carbonate deposits within the alluvial materials that cover the fault and are not offset, probably documenting at least 200,000 years of no motion. No reactivation of the detachment fault to disturb younger sediments is evident in outcrop along fairly nice exposures within the northern portion of the Santa Rosa Mountains. Isotopic evidence from the fault in the Borrego Springs area, where illite (crystalline clays) was dated by the K-Ar method and studied in detail, suggests that there has not been significant movement on the surfaces since about 12 Ma (M. Shafiqullah, pers. commun., 1989).

Another use of the term "detachment fault" in the Salton Trough is that of Gerard Bond and Kenneth Hudnut (e.g., Hudnut and others, 1993). In their usage of the term, the middle crust is detached or decoupled from the upper crust, thus allowing upper-crustal motion to occur within blocks within the brittle regime. Whether these modern-day zones of crustal movement are equivalent or genetically related to the detachment faults of Oligocene and Miocene age that are exposed around the margins of the Salton Trough is not well understood. Similar interrelationships between strike-slip faulting and detachment faulting are present in many other areas of the world. The Salton Trough provides a powerful insight into the similarities and differences between these two types of faults and how they are geometrically and genetically related.

SUMMARY

Regional detachment faulting has affected the entire Salton Trough region and developed an array of linked normal faults above a middle crustal zone of ductility (Fig. 14). Offset on these antiformal-synformal surfaces has developed major half grabens like the original Salton Trough. Zones of major weakness composed of pillows of ductile middle crust were also developed just as the sedimentary basins were. These zones of middle crustal weakness are thought to have largely localized the presence of different strands of the San Andreas system in Pliocene time. Similar interrelationships between crustal extension and strike slip faulting (e.g., Corona, 1993) are seen in many areas around the world.

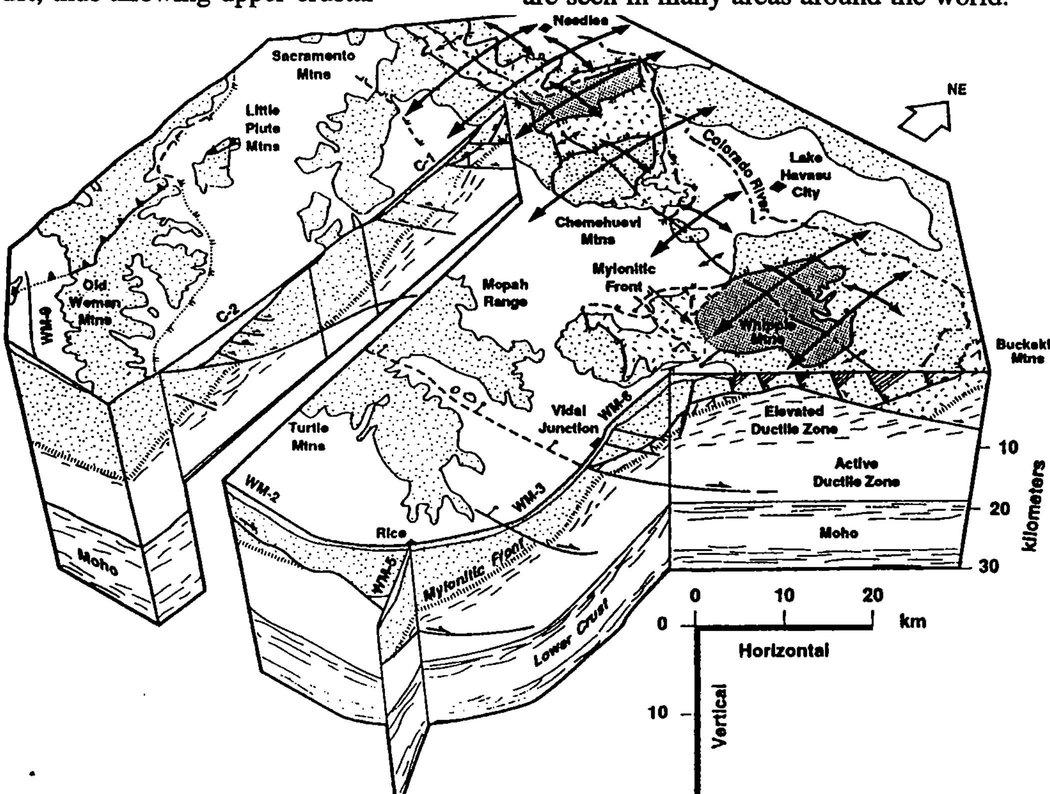

Fig. 14. Detachment fault-fold geometry and deep-crustal structure, Colorado River extensional terrane, as based on CALCRUST and reprocessed industry seismic lines. Multiple normal faults descend into middle crustal ductile zone and offset early-formed mylonitic zone. Active mylonitic zone remains sub-horizontal (parallel to earth's surface). As normal faults offset ductile fabric, exhumation of once middle-crustal rocks is a product of the offset on the normal faults and tilting over of the bounding normal faults. Similar deformation has affected both sides of the Salton Trough and the California Continental Borderland.