STRUCTURE AND HYDROCARBON EXPLORATION IN THE TRANSPRESSIVE BASINS OF SOUTHERN CALIFORNIA

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STRUCTURE AND HYDROCARBON EXPLORATION IN THE TRANSPRESSIVE BASINS OF SOUTHERN CALIFORNIA

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FIELD TRIP INTRODUCTION

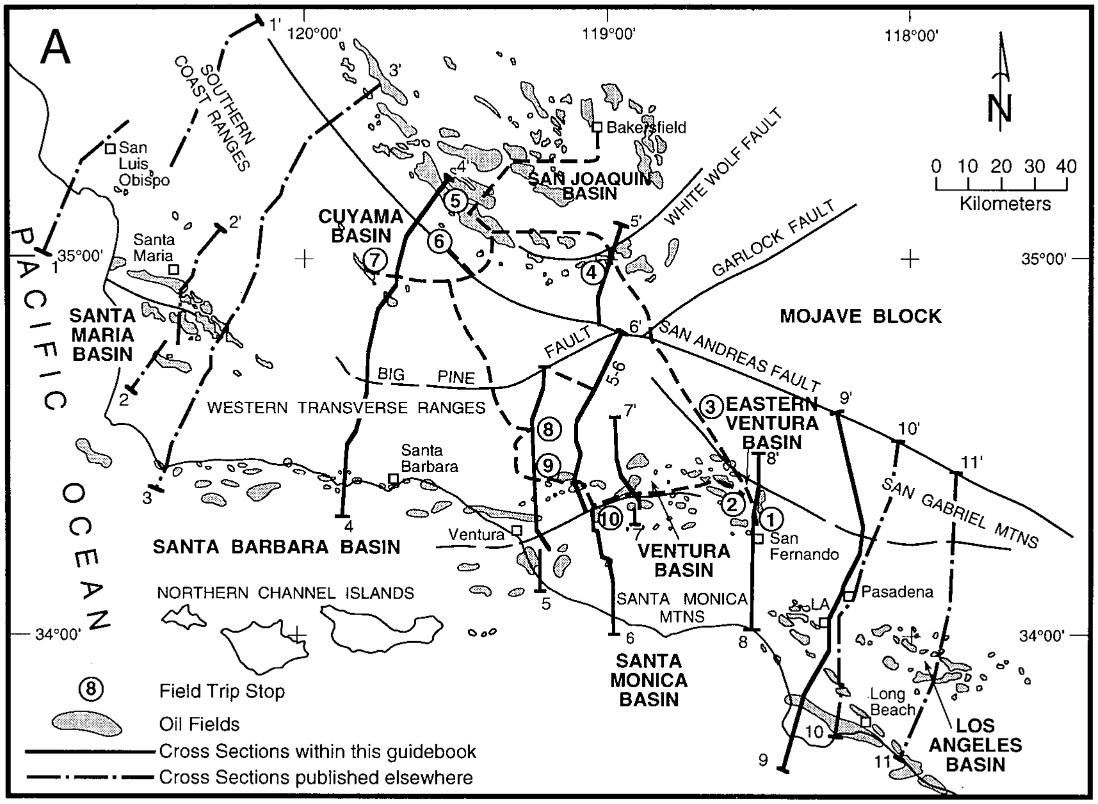
This field trip is an overview and reappraisal of the prolific oil basins of southern California (Fig. 1A) using exploration methods now commonly used in international exploration. As a result of the dramatic decline in oil and gas exploration in California during the last decade these mature and well known basins have received limited modern hydrocarbon research and it is hoped that our field trip and guidebook will outline some of the important aspects and questions of these intriguing petroleum systems. We have used balanced cross sections and other types of structural analyses integrated with basin modeling, geochemical and geophysical data to gain new insights into the structure, trapping mechanisms, and petroleum systems (Magoon and Dow, 1994) in a setting combining strike-slip and convergence (transpression). Southern California geology also has the scientific advantage, but societal disadvantage, of earthquakes (Fig. 1B) which provide useful data about the deeper structure which will be presented during the trip. Our field examples are in the eastern Ventura basin, Ridge Basin, southern San Joaquin basin, Cuyama basin and western Ventura basin as well as a transect of the western Transverse Ranges (Fig. 1A). During the field trip we will show that the southern California oil basins and petroleum systems have had a similar history during the last 2-3 Ma and there are a number of structural features common to all of the basins (Fig. 2A). Burial history modeling supported by geochemical data show that the petroleum systems have only recently begun (<5 Ma) to generate oil which provides us with a unique view of an active petroleum system.

The trip will also visit several producing oil fields giving us important details on trap style and timing, reservoirs characteristics, and recovery methods used in a complex setting commonly with heavy oil. There are ten stops which give the participant or reader a general view of southern California petroleum basins. Unfortunately lack of time prevents stopping in the prolific Los Angeles and Santa Maria basins and no attempt is made here to discuss the offshore basins. Since the field trip starts in San Diego and passes through the Los Angeles basin some summary information is provided in the beginning of the road log. The summary theme of the field trip is reflected in this guidebook paper which contains less text and more figures. For each of the basins visited the guidebook contains generalized surface and subsurface maps, restorable cross sections, stratigraphic columns, and burial history diagrams. These figures will provide a framework for understanding and discussing the interpretations of the structure and petroleum systems. Summaries are provided for the oil fields visited during the trip. We have relied heavily on the previous works of others and a large amount of unpublished data to make this guidebook. Generally we have cited only the most summary articles on an area or subject which contain detailed citations for those requiring additional information.

During the late Cenozoic a number of small but highly petroliferous basins developed along the boundary between the North American and Pacific plates in southern California (Fig. 1A). Plate motion during this period was dominantly right lateral with about 300 km of slip along the San Andreas fault (Crowell, 1975a) and with lesser amounts of slip occurring along a number of other faults (Crowell, 1981). It has been recognized for some time that the oil basins have a common history and geometric style but there are a number of different ideas on their structural style and evolution. Basin formation associated with extensional separation started in the late Oligocene and continued through the Miocene and early Pliocene (Crowell, 1987). Subsidence was regional with accelerated rates in the late Oligocene through early Miocene and again in the latest Miocene and early Pliocene. Marine conditions, mostly deep water in the coastal basins, prevailed in these basins during the Miocene and early Pliocene. Basin inversion resulting from crustal convergence occurs locally during the late Miocene and regionally during the late Pliocene and Quaternary. During the late Pliocene all of the onshore basins shoaled and now have significant amounts of Quaternary age non-marine deposits derived from uplift and erosion.

Large strike-slip offset along the San Andreas fault during the period of basin formation is well documented, but the role of strike-slip faults as basin forming structures remains problematic. Several models invoking a strike-slip pull apart (Crowell, 1987) or strike-slip and crustal rotation (Luyendyk and Hornafius, 1987) to explain the origin of the southern California basins are popular but have weaknesses: field data are commonly not consistent with the principal features of the model (see our discussion of the Los Angeles basin), the models are

in Patrick L. Abbott and John D. Cooper., eds., 1996,
Field Conference Guide 1996. Pacific Section A.A.P.G, GB 73,
Pacific Section S.E.P.M, Book 80, p.189-238.



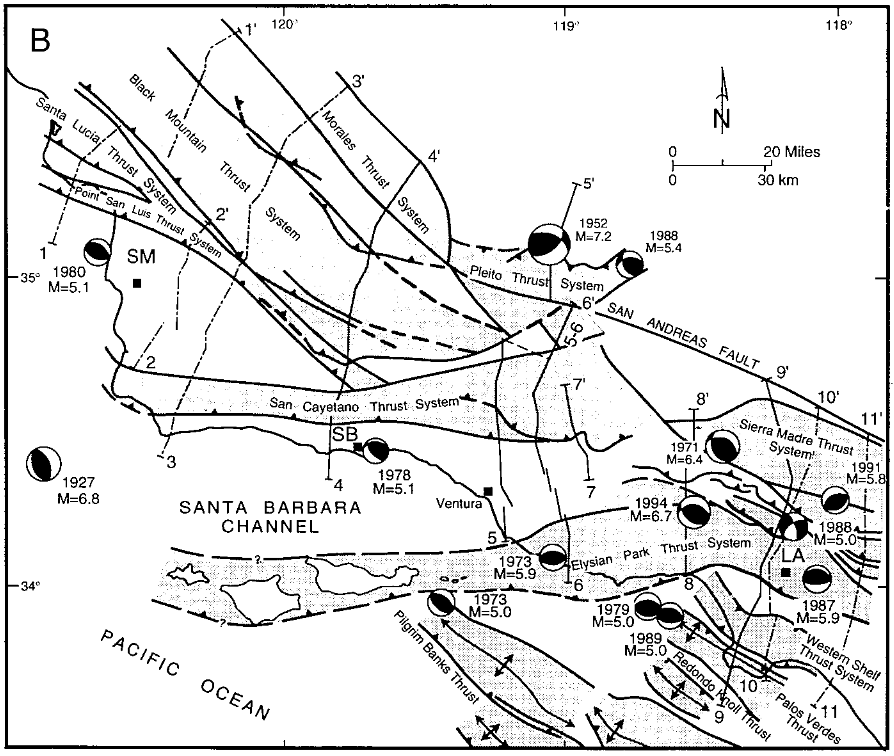


Figure 1A. Field trip location map. Santa Maria basin cross sections (1-1' and 2-2') are published in Namson and Davis (1990), western Transverse Ranges cross sections (3 -3', 4-4', 6-6' and 7-7' appear in Namson and Davis (1992), an earlier version of 8-8' is published in Davis and Namson (1994), an earlier version of Los Angeles basin cross section 9-9' is published in Davis et al (1989), and cross sections 10-10' and 11-11' remain unpublished.

Figure 1B. Map of major late Cenozoic thrust ramps of southern California and destructive compressional earthquakes (modified from Namson and Davis, 1992).

usually two dimensional illustrations of a three dimensional problem, and the models are too diagrammatic to pass the test of restorability. We make no attempt here to interpret Miocene and early Pliocene extension although the cross section restorations show features that should be considered in any interpretation. The field trip concentrates on the late Pliocene and Quaternary transpressive phase of basin development and our structural interpretation. We will also present our fold and thrust interpretation of many of the mountain ranges of southern California and contrast it with the earlier mega-flower structure interpretations proposed by Lowell (1972) and Harding (1976).

Southern California oil basins are renowned for their variety of trap styles ranging from anticlinal to primary pinchout to truncation traps. Much of the oil, especially in the supergiant fields, is trapped by anticlines with most if not all of the structural closure developed during late Pliocene and Quaternary convergence. A common trap style consists of anticlinal trends located along steeply-dipping basin-edge faults (Fig. 2A). During the field trip we will present evidence that these traps are the result of convergent overprinting of older normal faults (Figs. 2B-C) rather than the commonly cited wrench fault style (Fig. 2D).

Most of southern California's oil has its source in siliceous shale of the middle and upper Miocene Monterey Formation (Garrison and others, 1981; Issacs and Garrison, 1983; MacKinnon, 1989). Three of the basins we visit, Ventura, Los Angeles, and southern San Joaquin, have Monterey Formation as the primary source rock. The one, but important, exception during our trip is the Cuyama basin which has a latest Oligocene to early Miocene age source.

Monterey Formation oil is found in a great variety of reservoir types. Offshore, fractured siliceous shale, chert, and dolomite of the Monterey Formation are the predominant reservoirs, although sand reservoirs are locally important. Onshore, Monterey Formation oil is mainly in deep-water Monterey-age sandstone or Pliocene marine sandstone overlying the Monterey Formation. However, onshore Monterey Formation oil also occurs in reservoir types including non-marine Quaternary age sandstone units, pre-Monterey Formation sandstone beds, fractured crystalline basement, and fractured siliceous shale. Fracture development in the San Joaquin basin siliceous rocks is inhibited by clays and lower diagenetic grade, so instead of offshore production rates of thousands of barrels per day the onshore rates are typically hundreds of barrels per day.

Burial history modeling in this paper shows that Monterey Formation-sourced oil in southern California's onshore oil basins has been generated recently, starting 5 Ma or less. We infer that generation in the central Ventura basin may have begun only within the last 1 Ma.

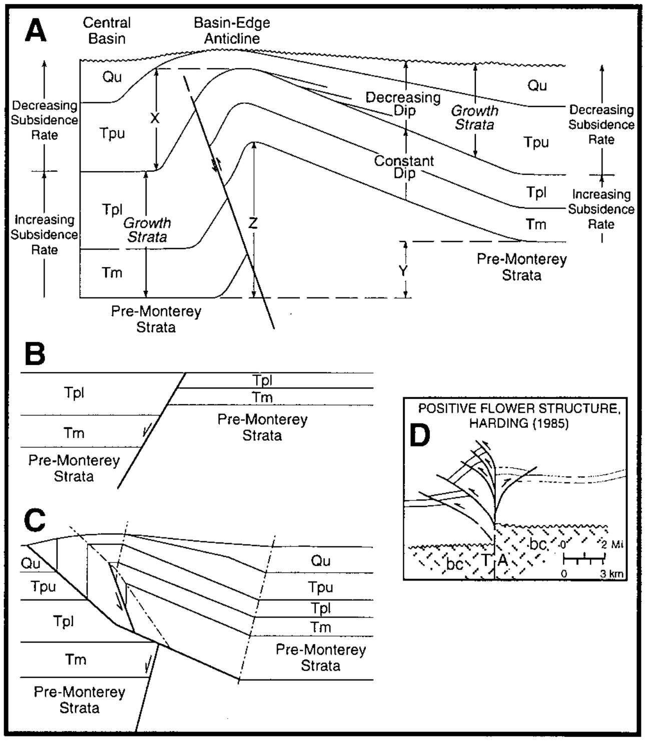


Figure 2A. Numerous basin-edge anticlinal traps in southern California have several common characteristics: basinward fold vergence developed during the late Pliocene and Quaternary, reverse faults along the steep limb, reverse faults lose slip into younger strata, Miocene and early Pliocene growth strata in downthrown block of reverse fault, and reverse faults have little or no strike slip during late Pliocene and Quaternary. Total structural relief (Z) consists of fold relief (X) and vertical separation across fault (Y). B and C show our two-stage model of an early normal fault later folded to explain the trap style. D shows a commonly cited wrench fault model for anticlinal trapping in southern California basins.

The Monterey Formation petroleum system in southern California basins is very interesting because it is active and the result of multiple deformations. Fault-controlled basin development influenced organic richness and many of the reservoir characteristics. Oil migration pathways are strongly controlled by structural relief which is the result of late Miocene and early Pliocene normal faulting overprinted by late Pliocene and Quaternary convergence.

Monterey Formation hydrocarbon generation in the Ventura and southern San Joaquin basins occurs at unusually great depths (4600-6100 m). Locally, as in the western Ventura basin very high sedimentation rates may have contributed to the great depth of oil generation. A striking feature of California's Monterey basins is the relative lack of gas fields and gas caps on oil fields. Our modeling shows that the Monterey Formation generally does not reach the depths required to generate significant gas volumes.

The unusually great depths of oil and gas generation result from low geothermal gradients caused by low heat flows (<1.25 HFU), and the very heat-conductive cover and bounding sequences to the Monterey basins.

California's Miocene and Pliocene age strata were commonly deposited in deep water, and most of the fields are sealed by deep-water mudstone. A possible consequence of the Monterey Formation's high present oil generation rates is that a number of large fields exist in spite of appearing poorly sealed. Placerita field (Stop #1) is probably a good example. Tar plugging of pore spaces is another unusual factor contributing to sealing in some of these fields.

Comments on Basin Modeling

Burial histories were run on ARCO's Genesis 4.0 program. Subsurface temperature data were taken from well log runs (with an average of three temperature-depth pairs per well) and corrected upward by 10%. Surface temperatures were assumed to be 68^{o}F. The predicted temperature profiles and maturation levels were corroborated in the Ventura basin by published heat flow data, at South Mountain oil field by published apatite fission-track data (Hathon, 1992), at Yowlumne oil field by measured reservoir temperatures, in the Cuyama basin by Rock-Eval Tmax data, and in the southern San Joaquin basin by maturity data. Only in the wells penetrating the southern San Joaquin basin source rock section was there a significant mismatch between predicted temperature profiles and corroborating data (Figure 17B), in particular vitrinite reflectance. Heat flow in our burial modeling is held constant through time because we consider the present state of knowlege to be poorly constrained.

Acknowledgments

We thank the following companies and individuals for technical and data support: ARCO International Oil and Gas Company allowed the use of its in-house Genesis 4.0 burial history program and Albert Holly of ARCO provided invaluable laboratory analyses and interpretation of oil samples. CoreLab provided geochemical data from their 1987 San Joaquin basin source rock study. Vintage Petroleum Company provided oil samples of the Wheeler Ridge and South Mountain oil fields. Well data was donated by UNOCAL, ARCO, Nuevo, and Enron. Joe Florez drafted most of the figures and additional drafting support was provided by ARCO. We would also like to thank Tom Hopps of Rancho Energy and the Ventura Basin Study Group (Hindel, R.J. and others, 1991) for providing their proprietary subsurface mapping of the Ventura basin.

DEDICATION TO MARTIN LAGOE

This trip and guidebook are dedicated to Professor Martin Lagoe who passed away December 26, 1995 in Austin, Texas. Martin was an excellent California field geologist and paleontologist who was always willing to integrate his specialty with other's areas of research-especially structural studies. Martin was a co-leader on past structural geology trips across the Transverse Ranges and we greatly miss his friendship and knowledge for this field trip. Presented throughout the guidebook are Martins' work which support and broaden the structural interpretations and are representative of his important additions to California geology. We all miss you Martin.

LATE CENOZOIC FOLD AND THRUST BELT OF THE WESTERN TRANSVERSE RANGES, SOUTHERN CALIFORNIA

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Introduction

This article is a summary of Namson and Davis (1988b). The Transverse Ranges of southern California consist of a series of young, east-west-trending basement-cored anticlinoria and synclinoria that cut across the northwest-trending structural grain of California. North-south shortening is active and documented by late Pliocene and Quaternary folds convergent faults, geodetically measured north-south convergence, and numerous compressive earthquake events with north-south-directed P-axes. A growing body of geologic, geophysical, and seismological data indicate that the Transverse Ranges and southern Coast Ranges are an active basement-involved fold and thrust belt (Namson and Davis, 1988a,b). These interpretations are consistent with measurements of the present-day stress field that indicate convergence between the North American and Pacific plates is expressed as a fault-normal compressive stress along the plate boundary (Mount and Suppe, 1987). Namson and Davis (1988a) presented a kinematic model suggesting the tangential component of motion between the plates is accommodated by pure strike slip along the San Andreas and associated faults, and the convergence is accommodated by folding parallel to the plate boundary and thrust faults with nearly pure dip-slip motions perpendicular to the plate boundary. Geophysical data show the majority of earthquakes occur above 15-20 km depth, and there are an east-west-trending high-velocity anomaly within the upper mantle (Humphreys et al., 1984) and a high-density gravity anomaly (Sheffels and McNutt, 1986) beneath the Transverse Ranges. Webb and Kanamori (1985) proposed a mid-crustal, subhorizontal crustal

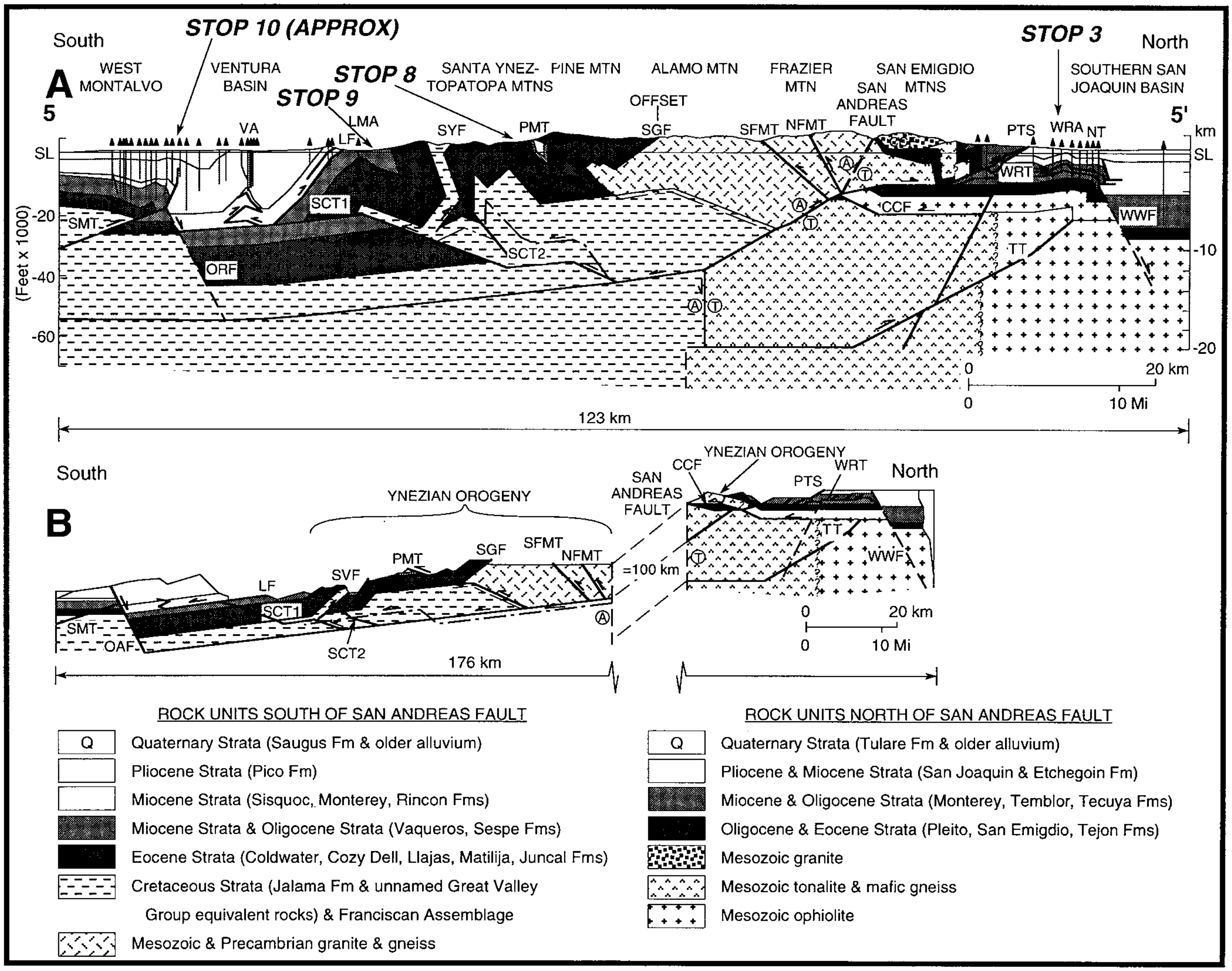

Figure 3A. Structural transect across western Transverse Ranges (Namson and Davis, 1988b). CCF = Caballo Canyon fault; LF = Lion fault; LMA = Lion Mountain anticline; NFMT = North Frazier Mountain thrust; NT = North Tejon oil field; ORF = Oak Ridge fault; PMT = Pine Mountain thrust; PTS = Pleito thrust system; SCT = San Cayetano thrust (SCT1 and SCT2 are splays); SFMT = South Frazier Mountain thrust; SGF = San Guillermo fault; SMT = South Mountain thrust; SYF = Santa Ynez fault; TT = Tejon thrust; VA = Ventura Avenue anticline; WRA = Wheeler Ridge anticline; WRT = Wheeler Ridge thrust; WWF = White Wolf fault. Circled A and T indicate strike-slip motion of San Andreas fault. B. Line-length restoration of late Pliocene through Quaternary compressive structures along cross section. Restoration shows late Eocene and Oligocene convergence (Ynezian orogeny), Miocene and Pliocene normal faults, and San Andreas strike-slip offset. San Andreas fault restores to a vertical fault, separating terrain now offset horizontally about 100 km since late Pliocene.

detachment to explain the low-angle, compressive earthquake mechanisms common to the area, and Bird and Rosenstock (1984) developed a kinematic model of crustal convergence and predicted mantle-lithosphere downwelling consistent with the observed upper-mantle seismic velocity and gravity anomalies.

Here we present a geologic model of the upper crust beneath the western Transverse Ranges based on a balanced cross section across the entire Transverse Ranges (Fig. 3A). The model interprets the area to be an actively developing fold and thrust belt that began to form during late Pliocene time (2-3 Ma). We interpret the major map-scale folds to be fault-propagation folds or fault-bend folds developed above thrust faults stepping upsection from a regional detachment that coincides with the floor of seismicity. The cross section and restoration (Fig. 3B) are used to estimate the amount of crustal convergence and the convergence rate across the western Transverse Ranges since late Pliocene time and to understand the relation between geologic structures and zones of seismicity.

Cross section (Fig. 3A)

On the south the section begins at the Montalvo oil field, which is trapped along the east-west Oak Ridge trend which is a series of north vergent anticlines along the southern edge of the deepest part of the Ventura basin. On the basis of fold shape the trend is interpreted to be a series of fault propagation folds above the postulated South Mountain thrust. The Oak Ridge anticlinal trend has folded the Oak Ridge fault which separates a thick upper Miocene to Pleistocene section on the north from a coeval but much thinner section to the south. The Oak Ridge fault is interpreted to be a Miocene to Pliocene north-dipping, normal fault (Namson, 1987) accommodating subsidence and sediment accumulation (Yeats, 1977).

The next major structure to the north is the Ventura Avenue anticline. The anticline has been interpreted to be rootless (Nagle and Parker, 1971). We show the fold as a series of wedge-shaped imbricate thrusts that are rooted at the base of the Miocene, and slip on the basal Miocene detachment is derived from the thrust responsible for the adjacent Lion Mountain anticline. The Lion Mountain anticline is interpreted to be a fault-bend fold associated with a ramp on a buried splay of the San Cayetano fault (SCT1) which steps up from a lower detachment within the Cretaceous strata to an upper detachment at the base of the Miocene sequence. Slip on the upper detachment of the fault-bend fold is partitioned between the wedge-shaped imbricates responsible for the Ventura Avenue anticline and the Lion Mountain fault, which is a bedding- plane back-thrust off the upper detachment.

To the north the cross section traverses the Santa Ynez-Topatopa mountains which are the overturned limb of a Quaternary age anticlinorium (Dibblee, 1982b; Yeats, 1983) that is interpreted to be two stacked anticlines in the subsurface. The deeper anticline is a fault-bend fold associated with the lower splay of the San Cayetano thrust (SCT1), and the upper anticline is a fault-propagation fold associated with an upper splay of the San Cayetano thrust (SCT2). The splays merge downward into a common detachment of the main San Cayetano thrust.

The Santa Ynez fault occurs along the north flank of the mountains and has been interpreted as either a right-slip fault, a left-slip fault, or a reverse fault with little or no strike-slip. Since the fault terminates at both the eastern and western ends of the Santa Ynez-Topatopa mountains we favor the reverse fault interpretation. We show the Santa Ynez fault as a north-vergent back thrust associated with a south-vergent late Eocene to early Oligocene thrust system (Ynezian orogeny) that uplifted the San Rafael high. The configuration of the Oligocene thrust system is shown in the restoration (Fig. 3B). The Santa Ynez fault is folded and cut by the Quaternary age San Cayetano thrust system and Quaternary deformation recorded along the Santa Ynez fault is thought to result from slip off the thrust system and shearing during folding

Northward the Pine Mountain thrust overrides the steep north limb of a syncline interpreted to be the front limb of a fault-propagation fold above a splay of the Pine Mountain thrust. The Pine Mountain thrust is shown to root downward into the same detachment as the San Cayetano thrust system. The hanging wall of the Pine Mountain thrust is composed of a thick sequence of Eocene and Miocene strata that rest unconformably on granitic and gneissic basement of Alamo and Frazier Mountains. The Miocene strata rest with angular discordance on moderately folded Eocene strata folded by the Ynezian orogeny.

The cross section intersects the San Andreas fault between the Big Pine and Garlock faults where it is a narrow zone with no evidence of significant dip-slip offset. North of the San Andreas fault is the north-dipping Caballo Canyon fault which is interpreted to be a south-vergent thrust that lifted the ancestral San Emigdio Mountains during the Ynezian orogeny. Along the north flank of the San Emigdio Mountains is the late Pliocene to Quaternary Pleito fault system, which consists of several south-dipping thrust faults. Well data show that the anticlines lie above thrust ramps many of which do not reach the surface. For example, the Wheeler Ridge thrust ramps up across the Miocene sequence to form the Wheeler Ridge anticline, but the thrust never breaks the surface. The splays of the Pleito fault system are shown to root at depth into one common detachment. Isopach mapping in the upper and lower plates of the main Pleito fault shows no evidence for strike-slip motion since Eocene time (Lagoe, 1987).

North of the Pleito fault system, the White Wolf fault separates upper Miocene and Pliocene strata of the San Emigdio Mountains from coeval but much thicker strata of the southern San Joaquin basin. Well data from the down-thrown side of the White Wolf fault show the presence of shallow-marine and lacustrine rocks at 3-4 km depth. Other well data show the White Wolf fault to be a south-dipping reverse fault within the steeply dipping north flank of an asymmetric anticline of the North Tejon oil field. We interpret the White Wolf fault to be a Miocene and Pliocene normal fault whose upper part has been subsequently folded. The broad, asymmetric North Tejon anticline suggests that it is a fault-propagation fold above a deep north-vergent basement thrust.

The cross section shows the splays of the Pleito thrust system root in a common detachment below the surface trace of the San Andreas fault. The shallow part of the San Andreas fault is interpreted to dip south and be detached in the upper plate of the Pleito thrust system. Shallow and deep crustal parts of the San Andreas fault are offset along two mid-crustal ramps of the Pleito thrust system compatible with other observations. The shallow south dip of the San Andreas fault is consistent with a positive gravity anomaly, tied to high-density rocks north of the fault, extending across the fault for 5-6 km. The topographically highest part of the western Transverse Ranges, the Mount Pinos and Frazier Mountain area, is located immediately above the conjectured strike-slip ramp along the San Andreas fault.

Conclusions

The present-day length of the cross section is 123 km, and the restored length is 176 km. The cumulative convergence (restored length minus deformed length) totals 53 km (30% shortening); 34 km south and 19 km north of the San Andreas fault. The cumulative convergence is a minimum because the section does not extend offshore to the southern boundary of the Transverse Ranges. The convergence values can be used to calculate average crustal convergence rates if the time convergence started is known. The onset of convergence is between 2.0-3.0 Ma yielding a convergence rate across the onshore part of the western Transverse Ranges from 17.6-26.5 mm/yr.

An important implication of crustal shortening above the mid-crustal detachment is that the lower crust and lithosphere must be shortened or subducted an amount similar to the upper crust. We favor the model of Bird and Rosenstock (1984), in which the lower crust and mantle lithosphere are subducted to account for the shallow-level crustal shortening. The shortening values in this study suggest that a 53-km-long slab of lower crust and lithosphere should have been subducted beneath the western Transverse Ranges during the past 2-3 Ma. (Fig. 4). The size of the postulated subducted slab compares favorably with the 60-km-thick high-velocity region that dips steeply to a depth of 100-150 km beneath the western Transverse Ranges, observed from seismic tomography (Humphreys et al., 1984).

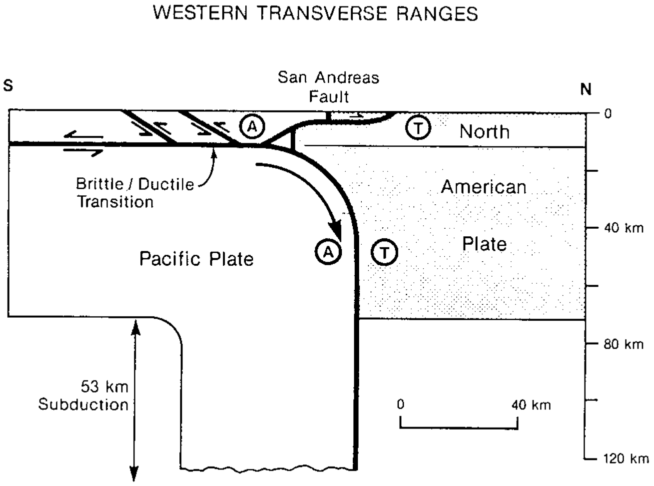

Figure 4. Schematic cross section showing how shortening below mid-crustal detachment of the Transverse Ranges is accommodated by subduction of lower crust and lithosphere of the Pacific plate. See text for a discussion of model. A and T indicate strike-slip motion of the San Andreas fault.

A final implication of the cross section is that strike-slip motion along the San Andreas fault and north-south compressive motion on thrusts are contemporaneous. At the plate tectonic scale, this model suggests that the transpressive strain between the North American and Pacific plates in the western Transverse Ranges is resolved into two components. The strike-slip component is parallel to the plate boundary (San Andreas fault and/or other strike-slip faults offshore). The compressional component is at a high angle to the San Andreas fault, parallel to the dip of thrust faults, and perpendicular to the axes of major late Pliocene to Quaternary folds. The resolution of displacements into orthogonal components is also recognized in the central California Coast Ranges (Namson and Davis, 1988a) and is consistent with the present-day compressive stress field, which is perpendicular to the San Andreas fault (Mount and Suppe, 1987).

ROAD LOG (FIRST DAY)

Take Interstate 5 north from San Diego towards Los Angeles. San Diego is located on a coastal plain between the northern Peninsular Ranges and the offshore San Capistrano basin. Here the coastline and structural grain is northwest trending parallel to the San Andreas fault system. The coastal plain is underlain by a gently tilted, locally folded, section of mostly shallow marine strata of late Cretaceous through Eocene age. Relative to similar age strata in southern California these rocks are remarkably undeformed. Eastward these westward-dipping rocks onlap the crystalline basement of the Peninsular Ranges indicating that uplift is the result of regional west tilting since Eocene time. The coastal plain extends northward to about the City of San Clemente where Interstate 5 departs the coastline. From San Clemente to the City of Santa Ana the freeway passes by hills underlain sedimentary rocks belonging to the southeastern margin of the Los Angeles basin. The section consists of upper Cretaceous through Eocene age mostly shallow marine deposits, Oligocene non-marine rocks, and Miocene age shallow to deep marine deposits and lesser amounts of igneous rock. To reach our first stop we will cross the northern portion of the Los Angeles basin (Fig. 1A). Although no stop is planned we have provided a geological summary of this famous oil basin.

Los Angeles Basin Summary

The Los Angeles basin is a small but prolific oil basin along the south side of the Transverse Ranges (Fig. 5A). Oil was first discovered in the basin at Brea Olinda in 1888 and since then 67 fields have been discovered including three supergiant fields (Wilmington, Long Beach and Huntington Beach). Present day basin EUR is about 9 Bbbl of oil and 7.6

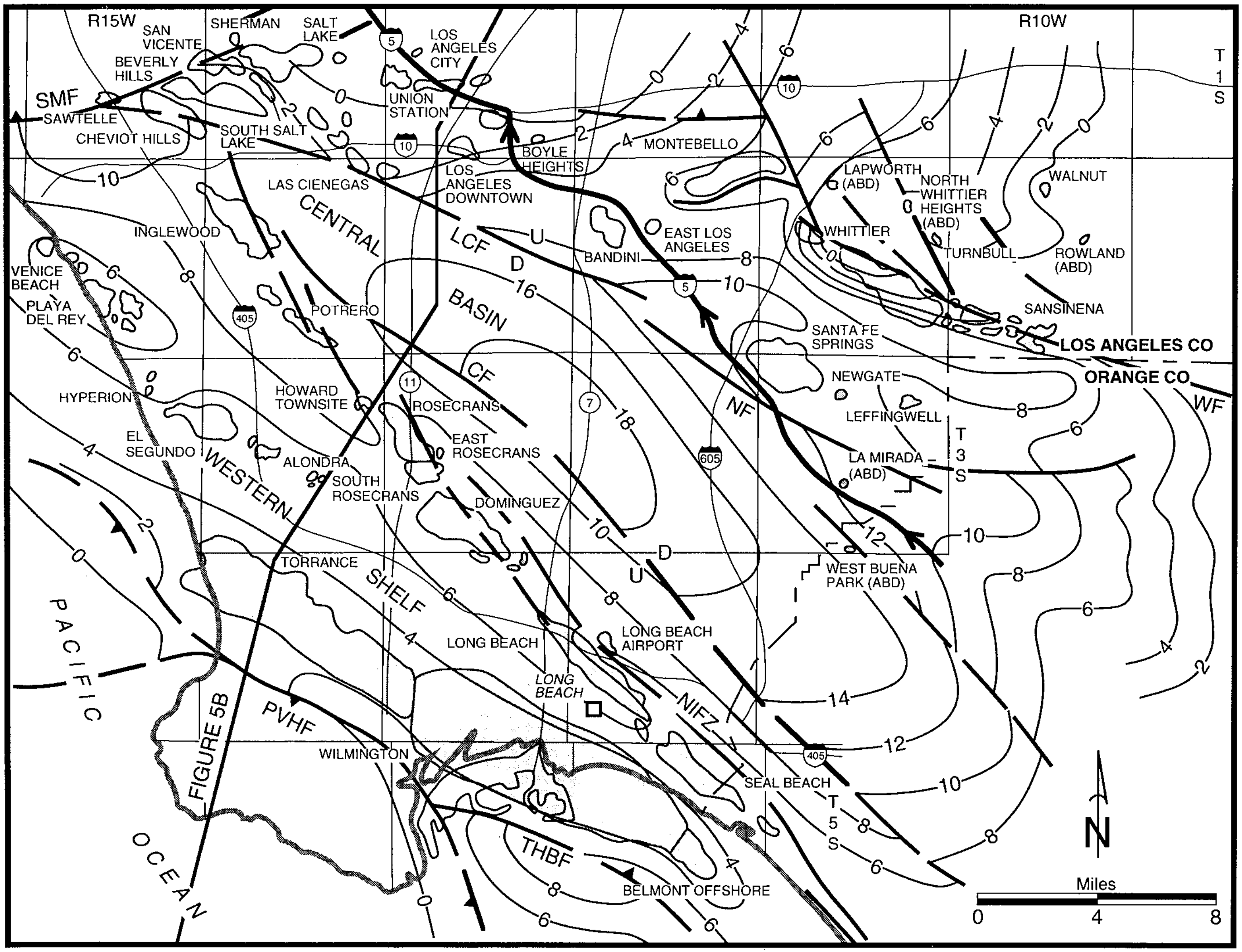

Figure 5A. Structure contour and oil field map of the Los Angeles Basin (modified from DOG, 1974; Wright, 1991). Contours on "base of Repetto" which lies just above the top of the Puente Formation (Monterey Formation equivalent). CF=Compton fault, LCF=Las Cienagas fault, NF=Norwalk fault, NIFZ=Newport Inglewood fault zone, PVHF=Palos Verdes Hills fault, SMF=Santa Monica fault, THBF=THUMS-Huntington Beach fault, and WF=Whittier fault.

Tcf of gas. Little exploration has taken place in the basin since the late 1970's mostly as a result of environmental and other regulatory restrictions. Much of the basin has been explored but significant potential probably remains as deeper and more complex parts of the basin, especially offshore, remain untested. For example the latest new field discovery was the offshore Beta field with 218 MOEB. See portions of Biddle (1991) for additional information on the Los Angeles basin.

The Los Angeles basin is a fault-controlled basin that began in the late Oligocene to early Miocene (Crowell, 1987). Its present configuration is the result of several phases of extension and sagging during the Miocene and Pliocene, a localized pulse of late Miocene convergence, and regional convergence during the late Pliocene and Quaternary. Figure 5A shows some of the major structures of the basin: western shelf, central basin deep, and the 5-6 km of convergent uplift along the northern edge of the basin. Figures 5B-C are a cross section and restoration across the entire basin and shows a basement-involved fold and thrust belt developed over a series of grabens and horsts (Davis and others, 1989).

The Los Angeles basin is filled with a thick section of Miocene through Quaternary age deposits (Fig. 6). Much of this section is the result of deep-water deposition by turbidity currents. Thick sandstone reservoirs with good to excellent porosity are interbedded with mudstone intervals that provide both trap seal and source beds in the case of the Monterey Formation equivalent rocks.

The cross section and restoration show our deep structural interpretation of many of the major structures of the basin. The Palos Verdes and Santa Monica Mountains anticlinoria are interpreted to be fault-propagation folds above seismically active thrust ramps that sole into a regional detachment at 15-20 km

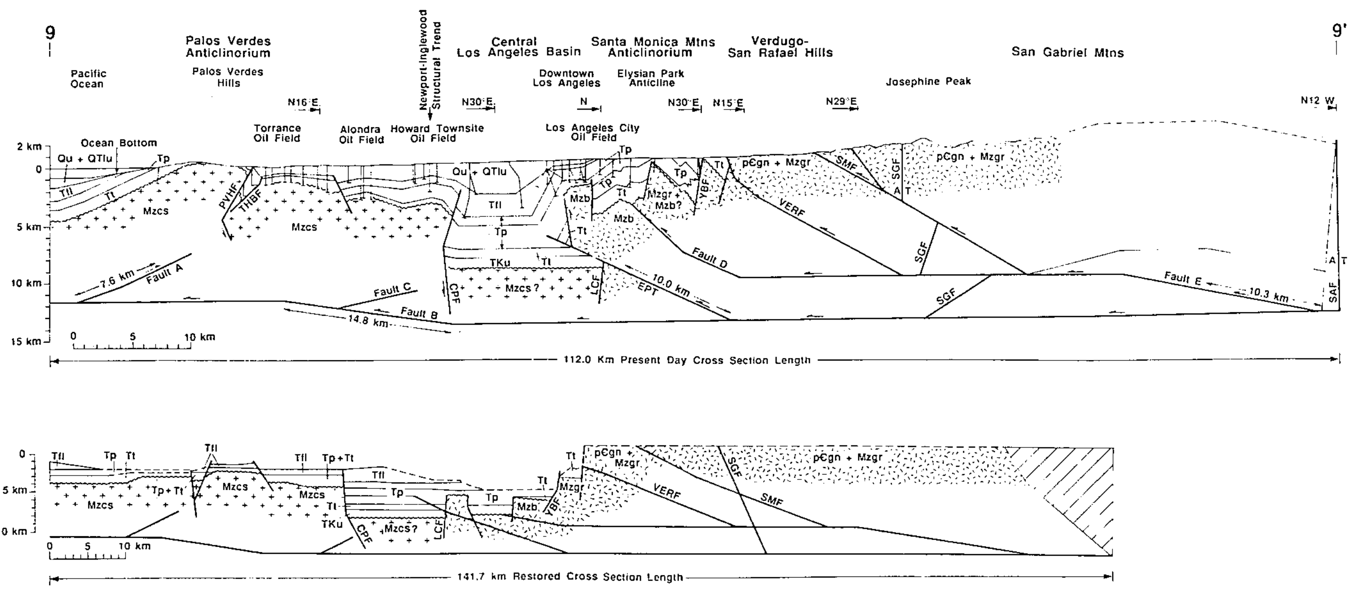

Figure 5B. Cross section across the Los Angeles basin showing fold and thrust interpretation of late Pliocene and Quaternary convergence (generalized from Davis et al, 1989). Fault abbreviations: same as Fig. 5A and CPF=Compton fault; EPT=Elysian Park thrust; LCF=Las Cienegas fault; SGF=San Gabriel fault; VERF=Verdugo-Eagle Rock fault; YBF=York Boulevard fault;. Geologic unit abbreviations: pCgn=Precambrian and possibly younger high-temperature metamorphic rocks; Mzgr=Mesozoic age plutonic rocks; Mzb=Santa Monica Slate and other metamorphic and crystalline rocks of the Santa Monica Mountains; Mzcs=Catalina Schist; TKu=undifferentiated upper Cretaceous and lower Tertiary strata; Tt=Topanga Formation and possibly older Tertiary age strata; Tm=Modelo and Puente Formations; Tfl=lower Fernando Formation; QTfu=upper Fernando Formation; Qu=undifferentiated Quaternary deposits. C. Line-length restoration of late Pliocene through Quaternary compressive structures along cross section. Comparison between deformed and restored sections yields 29.7 km of convergence since late Pliocene time (2.2-4.0 Ma) or 3.8-6.8 mm/yr. Restoration shows structure of the Los Angeles basin during late Miocene and early Pliocene was dominated by grabens and horsts.

depth. These thrusts do not reach the surface and the destructive 1987 Whittier Narrows earthquake (M=5.9) located under the Santa Monica Mountains anticlinorium probably occurred along the Elysian Park thrust. Thrusts uplifting the Verdugo Mountains-San Rafael Hills and the San Gabriel Mountains reach the surface.

Crowell (1987) postulated that the Los Angeles basin started as a strike-slip pull-apart basin in the early Miocene along the strike-slip Newport Inglewood fault and other faults. Luyendyk and Hornafius (1987), using paleo-magnetic data from the Transverse Ranges, propose the basin is the result of clockwise rotation of fault-bounded blocks during the middle to late Miocene. These models do not match the field data or explain the most compelling problems of the basin's development. The Newport Inglewood fault trend is not a basin-forming structure because the thickness of Miocene and Pliocene strata do not significantly change across the fault trend as shown in

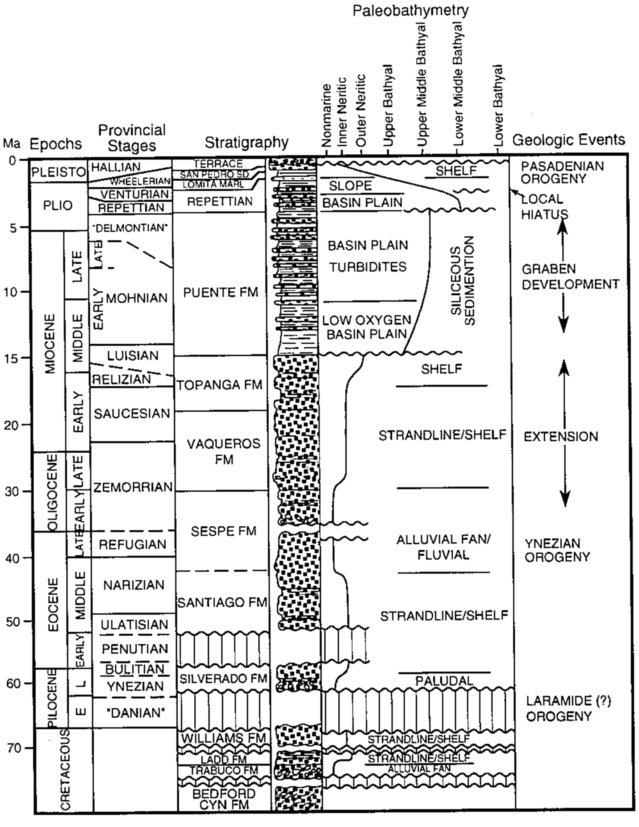

Figure 6. Generalized stratigraphic column of the Los Angeles basin showing paleobathymetry and important geologic events (Lagoe, unpublished).

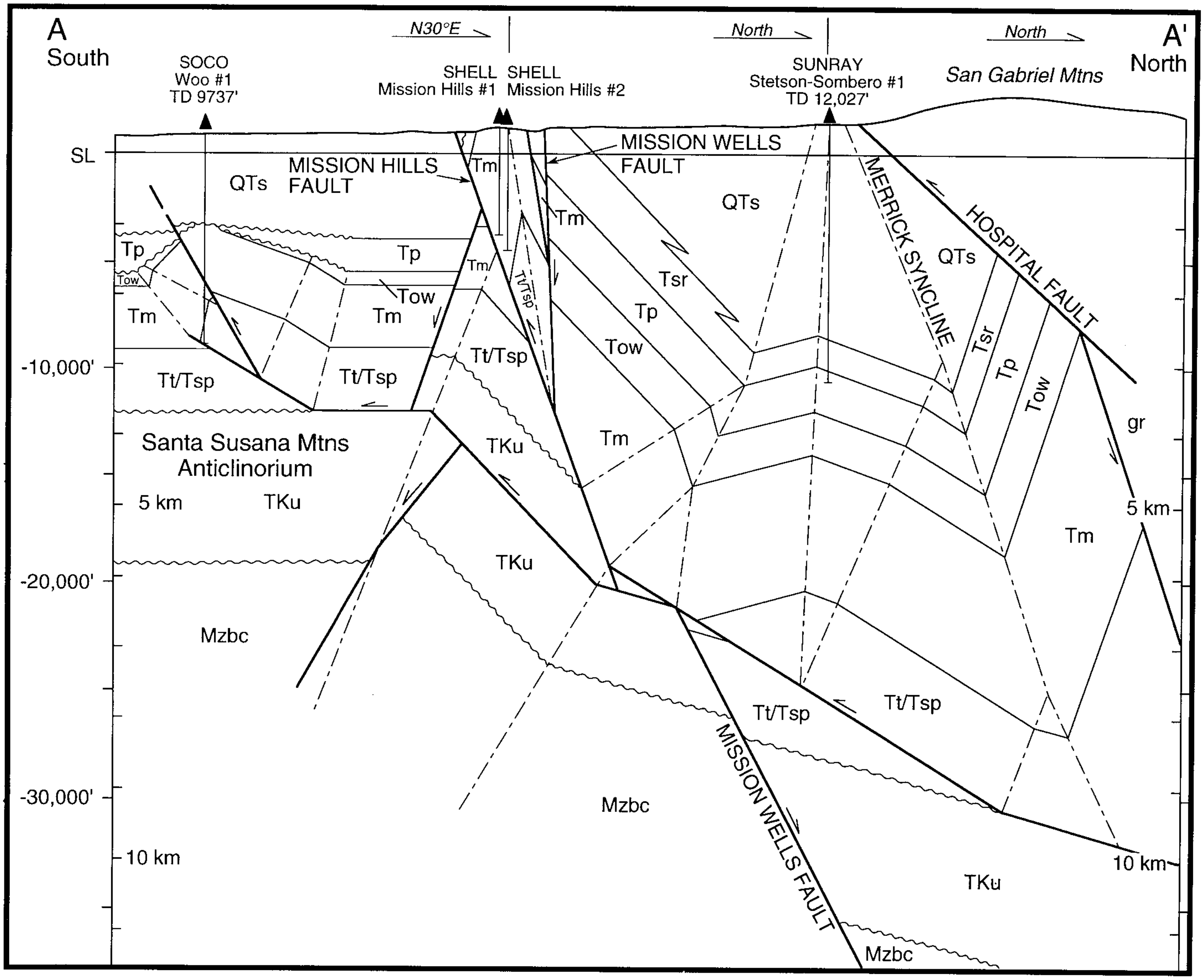

Figure 7. Cross section across the northern margin of the San Fernando subbasin showing basin inversion during the Quaternary. Abbreviations: Mzbc=Mesozoic-age plutonic rocks, TKu=undifferentiated upper Cretaceous and lower Tertiary strata, Tt/Tsp=undifferentiated Topanga and Sespe Formations; Tm=Modelo Formation; Tow=Towsley Formation; Tp=Pico Formation; Tsr=Sunshine Ranch Member Saugus Formation; QTs=Saugus Formation.

an abundance of published cross sections and maps (for example Wright, 1991). Well data show the deep central basin is bounded and formed by the vertical separation on the Compton-Los Alamitos fault trend on the south and the Las Cienegas-Norwalk fault trend on the north (Fig. 5B). Formation of the deep central basin cannot be due to strike-slip since neither of these fault trends have any demonstrated strike-slip offset and both faults die out to the southeast (Fig. 5A).

Go northwest on Interstate 5 which diagonally crosses the northwest portion of the Los Angeles basin (Fig. 5A) and San Fernando Valley (Fig. 8A). At the join of the San Diego freeway (405) and Interstate 5 are the Mission Hills where roadcuts expose steeply-dipping beds of the Monterey, Towsley and Saugus Formations. Figure 7 is a nearby cross section under the Mission Hills showing recent convergence along the northern San Fernando Valley. The Mission Hills and Hospital faults had surface rupture during the 1971 San Fernando earthquake (Oakeshott, 1975; Whitcomb and others, 1973) and both faults are segments of the Sierra Madre thrust system which uplifts the San Gabriel Mountains. The Mission Hills thrust fault ramps up, displaces and rotates the older Mission Wells fault. The Mission Wells fault is interpreted to be a late Miocene and Pliocene normal fault belonging to the Oak Ridge fault system which lies along strike to the northwest. If so the thicker Miocene and Pliocene units north of the Mission Wells fault belong to the eastern Ventura basin.