Structure and Hydrocarbon Exploration in the Transpressive Basins of Southern California
Jay S. Namson, San Clemente, CA
Thomas L. Davis, Ventura, CA
Stuart Gordon, Vintage Production, CA, LLC
Guidebook for Field Trips #4 & #6
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Namson and Davis, 1988a, Seismically active fold and thrust belt in the San Joaquin Valley, central California: GSA Bull., V.100, p. 257-273. (Permission to publish granted by Geological Society of America)
A few comments about the organization of field trips # 4 and # 6: In the past this was one trip over two days (San Diego, 1996; Long Beach, 2012), but is now two separate trips. The trips will use the same guidebook and visit essentially the same stops as the earlier trips but in a different order. These trips will start in Bakersfield each morning and return to Bakersfield each evening. At the end of this guidebook is a map showing locations of present stops.

Field trip # 4 is a transect across the western Transverse Ranges and, for the most part, is along Highways 166, 33, and 150. Field trip # 6 is a transect across the central and western portions of the Transverse Ranges and, for the most part, is along Highway 166, Interstate 5, and Highway 14.

The authors wish to thank the Geological Society of America for allowing the use of the two figures on the guidebook cover and reprinting of Namson and Davis, 1988b, with comments and replies, that appears at end of this guidebook.

Welcome to our field trip,

Jay Namson
Thom Davis
Stuart Gordon
Field Trip # 4 (April 30, 2014, 8:00-17:00)

Stop 1, San Andreas fault, see page 220 (was stop 6).

Stop 2, Cuyama basin and Russell Ranch oil field, see page 222 (was stop 7).

Stop 3, Santa Ynez-Topatopa Range, Santa Ynez fault, and western Transverse Range fold and thrust belt, see page 229 (was stop 8).

Stop 4, Ojai Valley and deformed northern margin of the Ventura basin, see page 229 (was stop 9).

Stop 5, Central Ventura basin and South Mountain oil field, see page 230 (was stop 10).

Return to Bakersfield

Field Trip # 6 (May 01, 2014, 8:00-17:00)

Stop 6, West side of the San Joaquin basin, Temblor Range, and Midway Sunset oil field, see page 216 (was stop 5).

Stop 7, Southern San Joaquin basin and Wheeler Ridge oil field, see page 210 (was stop 4).

Stop 8, Ridge basin (optional), see page 205 (was stop 3).

Stop 9, Eastern Ventura basin, Towsley Canyon, and the Santa Susana Mountains, see page 203 (was stop 2).

Stop 10, Eastern Ventura basin and Placerita oil field, see page 200 (was stop 1).

Return to Bakersfield
STRUCTURE AND HYDROCARBON EXPLORATION IN THE TRANSPRESSIVE BASINS OF SOUTHERN CALIFORNIA

Thomas L. Davis
Davis and Namson
Valencia, CA

Jay S. Namson
Davis and Namson
Valencia, CA

Stuart Gordon
ARCO International
Plano, TX

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, geochronological and geophysical data to gain new insights into the structure, trapping mechanisms, and petroleum systems (Magoo 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, reservoir 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 petrolierous 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
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 siliciclastic 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 siliciclastic 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 siliciclastic shale. Fracture development in the San Joaquin basin siliciclastic 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°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 Yowumne 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 knowledge 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

Jay Namson and Thom Davis
Davis and Namson Consulting Geologists
Valencia, CA

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, geocetically 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 = Pletio 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 3-6 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).

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 Miocene 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 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 Cienegas fault, NF=Nerwalk 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; Tff=lower Fernando Formation; QTu=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.
Figure 8B is a regional cross section that parallels our present route, and shows an interpretation of the 1994 Northridge earthquake (M=6.8) and structure of the upper crust (Davis and Namson, 1994). We interpret the Santa Monica Mountains and Santa Susana Mountains anticlinorium as crustal-scale fault-propagation folds above blind thrusts. Movement along the Pico thrust, making the Santa Susana Mountains anticlinorium, generated the Northridge earthquake. The Elysian Park and Pico thrusts flatten into a mid-crustal horizontal detachment. An alternative model by Yeats and Huftile (1994) places the earthquake on the Oak Ridge fault which they interpret to dip steeply into the mid-crust.

Figure 8A. Structure contour and oil field map of the eastern Ventura Basin (modified from Hindle et al, 1991 and DOG, 1974). Contours on top of Modelo Formation (Monterey Formation equivalent). Abbreviations: HF=Hospital fault; PA=Pico anticline, SSF=Santa Susana fault.

Figure 8B. A regional cross section across the Santa Monica and Santa Susana Mountains showing a fold and thrust belt interpretation of the 1994 Northridge earthquake (modified from Davis and Namson, 1994).
Take Interstate 5 across the northwest portion of the Los Angeles basin. Cross the San Fernando Pass which is the break between the San Gabriel Mountains on the east and the Santa Susana Mountains on the west. Take the Antelope Valley Freeway east off of Interstate 5 and exit at Sierra Highway. Enter the Placerita oil field via the main entrance off the Sierra Highway. The field is private property and hazardous, and permission must be obtained from ARCO before entering the field. Take a field road up to drilling pad near the wellhead of Kennedy #11-22.

Stop #1, Eastern Ventura Basin and Placerita Oil Field

From the oil field is a sweeping view of the San Gabriel Mountains to the east, and to the west the north side of the Santa Susana Mountains with outcrops of upper Miocene and Pliocene clastic rocks—some equivalent to the Placerita oil field reservoirs. These outcrops are along the Pico anticline which will be visited at Stop #2 (Fig. 8A). The oil field produces from the lower Pliocene Kraft zone of the Pico Formation derived from erosion of the crystalline rocks of the San Gabriel Mountains. Hike up a short distance to the top of the ridge behind the well pad and observe the linear northwest-trending canyon formed by erosion along the San Gabriel fault. Steeply-dipping beds of the non-marine Saugus Formation are exposed along the trace of the fault. In the subsurface the fault dips about 60° to the northeast and its most recent motion is reverse separation. Here the San Gabriel fault is the eastern termination of the petroliferous Ventura basin and to the east is the Soledad basin—a mostly non-marine basin of late Oligocene through late Miocene age. To the northwest, on the skyline, is the Ridge Basin which formed along the San Gabriel fault during late Miocene right strike-slip (Cowell, 1975a, b). The Placerita Canyon area is also noteworthy because commercial quantities of gold were discovered in 1842, six years before the famous gold rush of the northern Sierra Nevada.

Placerita's oil is probably sourced from the Monterey Formation (Fig. 9A), and ARCO proprietary geochemical data suggest that the gravity of the oil is inversely related to the degree of biodegradation. Placerita sits on a high block which lacks Modelo Formation (Monterey Formation equivalent). Burial history modeling shows that all of the Neogene strata are extremely immature for hydrocarbon generation, which is corroborated by the high porosity and permeability of the reservoir rocks.

Placerita's oil was sourced from the eastern Ventura basin deep, located 10-15 km to the northwest (Fig. 8A) and Figure 9B shows a burial history from that area. This thermal modeling suggests that the top of the thick Modelo Formation is just now beginning oil generation (Figs. 9B-D). The base of the Modelo Formation began oil generation during rapid deposition of the Saugus Formation, starting approximately 2 Ma (Yeats and others, 1994). It may be generating gas today, accounting for the free gas (as gas zones or gas caps on oil fields) that occurs in several eastern Ventura fields (Castaic Junction, Aliso Canyon, Oak Canyon, and Honor Rancho). Free gas is uncommon elsewhere in the onshore Ventura basin, possibly because Monterey Formation maturity is not high enough to cause gas generation.

Oil migration paths to Placerita field from the generation area probably changed markedly in the last 1 Ma, due to crustal shortening and uplift. Miocene and Pliocene isopach maps (Yeats and others, 1994) suggest that before shortening started, the basin was dominated by a southwest dip, so that any lower Modelo Formation oil that was generated migrated mainly north and east toward the San Gabriel fault. Present-day structure maps of the Modelo Formation (Hindel and others, 1991) show that migration paths are now much more tortuous and shorter. Large amounts of oil are now migrating into the crests of the anticlines containing Newhall-Potrero, Castaic Junction, and other fields where the monoclinal dip previously predominated.

Summary of Placerita Oil Field

Tom Berkman
ARCO Western Energy Company
Bakersfield, CA

This article is a summary of Berkman (1994). Placerita oil field was discovered in 1920 but full-scale development did not take place until 1949 when light oil was discovered in an area known as Confusion Hill. The discovery started one of the biggest town-lot leasing booms in California history as much of the area had been subdivided into tiny parcels (71 acres sold as 80 acres). At one point in 1949, 48 rigs were working and production peaked at 36,000 BOPD from 100 wells. Production declined rapidly and many of the leases were abandoned and left in disarray with some of the old tanks and corroded wellheads still remaining. Presently the field produces approximately 3300 BOPD (12° API) with cyclic steaming and steamflood injection support. Here we discuss the results of ARCO's geological and reservoir analyses of the main producing interval, the Pliocene lower Kraft zone, and completion and steam management strategies developed to optimize recovery from the complex reservoir.

A structure contour map shows the field is a west-dipping homoclinc bounded on two sides by faults (Fig. 10A). On the north is the San Gabriel fault, which is actually a complex zone of north-dipping faults, formed during several episodes of deformation involving right strike-slip with normal separation followed by reverse separation. Several strands of the fault cut the upper Kraft zone and Saugus Formation
Figure 9A. California oil families showing Placerita, Wheeler Ridge, and South Mountain fields. Courtesy of Albert Holba. ARCO Exploration and Production Technology Company.

Figure 9B. Eastern Ventura kitchen burial history showing transformation ratio (Φ). Castaic field vicinity. Composite of Exxon NL&F #18, 53, and 78 wells. Heat flow = 1.1 HFJ.

Figure 9C. Eastern Ventura kitchen hydrocarbon generation rates versus depth.

Figure 9D. Eastern Ventura kitchen Monterey oil generation rates versus time.
in wells along the northern margin of the field. The west-dipping Whitney Canyon reverse fault bounds the field on the east and oil-stained cores and seeps east of fault show it is a broken or leaky trap. Miocene movement along the San Gabriel fault may be responsible for Placerita anticline (Fig. 10A) which existed as a high during the Pliocene and restricted deposition of the lower Kraft zone. The west edge of the field is defined by a very irregular oil/water contact (Fig. 10A) which varies by about 200 m in less than 1.6 km, and equivalent reservoir sands are productive in the north while wet in south. The field has an edge-water drive, with a handful of wells in the southwest through the oil-water contact.

The Placerita oil field has reservoir characteristics comparable to other fields in California, such as Midway Sunset and Kern River, where steam flooding has been extremely successful at maximizing ultimate recovery. At Placerita reservoir steam heating lowers the oil viscosity from about 10,000 cp at 90°F to 13 cp at 300°F. Understanding the complex lower Kraft reservoir is critical to the success of the steamflood and although intra-field correlations are difficult they are solvable by integrating all available geological, engineering and production data. Early interpretations of the lower Kraft zone as a continuous reservoir with a few shale interbeds were ideal for steamflooding, however, additional drilling shows these sands are independent packages which may or may not be connected at some point in the field.

Excellent exposures of the lower Kraft zone are along the Sierra Highway near the Tunnel area of Newhall field, and in old roadcuts and cliff exposures east of Highway 14 via the gated Remson Street underpass. The Sierra Highway locality contains spectacular exposures of large-scale channel facies hundreds of feet high and the irregular terrain allows three-dimensional views. In the subsurface, we have subdivided the lower Kraft zone into four main sandstone bodies each with separate subzones (Fig. 10B). These bodies have linear to lobate forms up to 50 m thick separated by discontinuous shale beds. Figure 10B shows a complex reservoir consisting of numerous amalgamated channels, sudden facies changes, interbedded sand-shale sequences, and onlap against an Eocene paleo-high (Placerita anticline) located to the south. It is evident that individual channelized sandstone bodies in the lower Kraft are of limited lateral extent. For example, the “Sand 2” channel is approximately 200 m wide in the center of the field. The shale is even less continuous than the sandstone bodies. The shale records interchannel levee and overbank fine-grained deposition, which were sometimes eroded by the next channel system.

Figure 10A. Structure contour map of the Placerita oil field. Contours on the top of lower Kraft zone which is the main producing horizon.

Figure 10B. Lower Kraft zone type log for the Placerita oil field. See text for discussion of subdivisions and facies.
Temperature logs indicate that the shale forms effective seals and baffles for confining steam. In a single five spot steamflood pattern, it is often necessary to complete surrounding injectors in different zones to achieve flooding of all perforated zones in corresponding producers.

The lower Kraft zone was deposited in middle to outer neritic water depths by rapid turbidite deposition based on fossil (mainly foraminiferal) and lithologic data, regional setting, and stratigraphic position. The lower Kraft facies is similar to facies of the late Miocene Puente Formation of the Los Angeles basin where nested channels and sediment lobes were formed along the shelf-edge and slope (Lyons, 1991). Microfossils recovered from core and ditch samples from the lower Kraft zone place it in the “middle Pico” member of the Pico Formation (Dumont, 1990a,b). Foraminiferal checklists from Dumont were compared with published lists from exposures of “type” Pico deepwater deposits in nearby Pico Canyon (Winterer and Durham, 1962) where water depths are significantly deeper than the range of depths for forms at the Placerita field. The Pico Canyon section indicates prograding up section from water depths of 600–900 m to a depth of 200–500 m reflecting regional regression of the Ventura Basin.

Lower Kraft sands at the Placerita field are similar in thickness to coeval sands at Pico Canyon and in the Newhall Potrero oil field. This is in contrast with the gross Pico thickness which decreases from 1,500 m in the Newhall-Potrero field to about 100 m at Placerita field. Most of the decrease occurs in the upper part of the formation as shown by detailed mapping of coarse clastic beds by Winterer and Durham (1962). They were also able to show that the contact between the Pico and overlying Saugus Formation occurs at lower and lower stratigraphic levels eastward from Pico Canyon implying that the Pico sands at the Placerita field and those in Pico Canyon may be depositionally contiguous and time transgressive.

Convergent folding and faulting in the east Ventura basin initiated during the late Pliocene (Yeats and others, 1994). Ongoing tectonism resulted in pulses of coarse clastic sediment into the basin and structural warping and faulting occurred along the basin edges as well as sediment loading within the basin. Regression along the basin edge caused fan deltas to prograde across the exposed shelf with turbidite complexes formed at the distal toes of the deltas. Uplift and erosion along the San Gabriel fault resulted in a complex of nested channel fill deposits in the Placerita field.

Take the Antelope Freeway west to the intersection with Interstate 5 and take the Interstate north. Outcrops along the highway are Towsley and Pico Formations along the northeast limb of the Santa Susana anticlinorium. To the north the Santa Clara Valley is underlain by a thick sequence of Quaternary non-marine deposits (Saugus Formation), the erosional products of crustal convergence and uplift. Exit at Calgrove Road and go left to the Ed Davis Regional Park.

**Stop #2, Eastern Ventura Basin, Towsley Canyon and the Santa Susana Mountains**

Park at the upper parking area of Ed Davis Regional Park (Fig. 11A). We will hike about one kilometer up Towsley Canyon to the core of the Pico anticline (Note as of March 1996 the upper part of the canyon was still closed to visitors). Towsley Canyon is located along the northeast side of the Santa Susana Mountains which have uplifted and exposed rocks of the petroliferous eastern Ventura basin. Here is a good place to consider the short and long term effects of the 1994 Northridge earthquake. The high ridge line to the southwest is Oat Mountain which was uplifted about one meter during the earthquake and the nearby steeply-dipping strata belong to the north limb of the Santa Susana Mountains anticlinorium which Davis and Namson (1994) interpret to be the result of numerous movements on the Pico thrust.

![Figure 11A. Geologic map of the Towsley Canyon area, northeastern Santa Susana Mountains (modified from Winterer and Durham, 1962). Dip domains bend around normal faults showing the influence of older basin structure during basin inversion. Abbreviations: Tm=Modelo Formation, Ts=Towsley Formation, Tp=Pico Formation, Qu=undifferentiated alluvial strata.](image-url)
Surface mapping (Winterer and Durham, 1962) combined with a number of deep exploration wells drilled in the eastern Ventura basin allow the construction of deep cross sections and subsurface maps in this complex area. During Miocene and Pliocene time the eastern Ventura basin was a graben between the Oakridge fault system and, on the east, the San Gabriel fault and an unnamed subsurface fault (Fig. 11B). Subsequently the Santa Susana Mountains anticlinorium propagated basinward to the unnamed normal fault creating a curvature in the fold geometry (Fig. 11A). The Santa Susana fault is exposed near the crest of the Santa Susana Mountains southwest of Towsley Canyon. The fault dips to the northeast and the Pico anticline and Towsley Canyon lie in the hanging wall of the fault. During late Pliocene and Quaternary convergence the thickest portion of the eastern Ventura basin was thrust southward over the basin margin by the Santa Susana fault. Davis and Namson (1994) propose that the Santa Susana fault formed prior to being folded by the anticlinorium since the north limb of the anticlinorium folds both the hanging wall and footwall of the Santa Susana fault (Fig. 11B). For an alternative interpretation of the structure of the eastern Ventura basin see Yeats and others (1994). The Aliso Canyon oil field (59 MOEB) is in the footwall of the Santa Susana fault (Fig. 8A), and the previously presented basin modeling (Figs. 9B-D) suggest the field was charged with hydrocarbons during basin inversion.

Deep erosion of Towsley and several other canyons along the northeast flank of the Santa Susana Mountains provide easily accessible transects through the basinal portions of a typical southern California coastal basin. Canyon exposures provide an excellent record of deep marine deposition during the late Miocene and Pliocene, basin shoaling beginning in the late Pliocene, and Quaternary non-marine deposition. Winterer and Durham (1962) in their pioneering work on deep-water deposition provide an excellent map, field descriptions, and paleoenvironmental interpretation of this area. Upstream (west) from the upper parking lot the Pico Formation grades downward to interbedded sandstone, mudstone and conglomerate of the Towsley Formation. About 500 m upstream from the upper parking area Towsley Canyon becomes steep-walled and narrow with excellent exposures of the lower part of the Towsley Formation. Paleontological data show the lower unit

![Diagram](image-url)

Figure 11B. Cross section across the Santa Susana Mountains showing inversion of the eastern Ventura basin. Abbreviations: Ku=upper Cretaceous strata, Tep=undifferentiated Paleocene and Eocene strata, Tt=Topanga Fm; Ttv=Topanga Fm igneous unit; Tm=Modelo Formation, Tto=Towsley Formation, Tp=Pico Formation, QTs=Saugus Formation.
was deposited at outer neritic to bathyal depths, and Winterer and Durham (1962) proposed this coarse-grained unit was a turbidite deposit. Stitt (1984) mapped out the lower Towsley Formation showing a pattern of southwest-trending alternating fan and interfan deposits that emanated from the area of the San Gabriel fault (Fig. 11C). Crystalline rock clasts suggest the fan system was derived from a horst block along the San Gabriel fault, or the fan system was offset by the fault from its source in the western San Gabriel Mountains (Crowell, 1952).

Beyond the gorge the Towsley Formation is underlain by silty shale of the Modelo Formation which is exposed in the core of Pico anticline. Numerous oil seeps occur along the crest of the anticline (Fig. 11A) which was the site of some of California’s earliest exploration efforts. In 1876, in nearby Pico Canyon, Pacific Coast Oil Company completed California’s first commercial oil well.

Take Interstate 5 north across the Santa Clara Valley. The deepest part of the eastern Ventura basin is just west of the intersection of Highway 126 and Interstate 5 (Fig. 8A). Outcrops east of the intersection are folded Saugus Formation along the San Gabriel fault and the fault crosses Interstate 5 at the Honor Rancho. Just before climbing the steep grade look west (left) up a small canyon for resistant outcrops of the Violin Breccia, a late Miocene age scarp deposit along the San Gabriel fault. We are now entering the lowermost portion of the Ridge basin (Fig. 12A), and roadcuts along the steep grade expose the upper Miocene Castaic Formation-a deep marine deposit. Exit the interstate at Templin Highway and go east to the intersection with the Old Ridge Route

**Stop #3 (optional) Ridge Basin**

At the intersection of the Old Ridge Route and Templin Highway are excellent road-cut exposures showing the marine to non-marine transition within the Ridge Basin and a nearby overview of the southern Ridge Basin (Fig. 12A). The marine to non-marine transition is within the Marple Canyon Sandstone Member, the lowermost portion of the Ridge Route Formation. Marine strata are exposed south and east of the intersection along the Old Ridge Route and Templin Highway and consist of slope facies and channel and interchannel turbidites with numerous slump-folded beds and other soft sediment structures. West and north of the intersection and above the marine beds are non-marine fluvial-deltaic deposits which prograded over deep marine as the basin filled.

Climb the small hill north of the intersection for a view of the southern Ridge basin. To the east is Castaic Canyon which exposes the lower portion of the Ridge Basin. Outcrops across Castaic Canyon are the upper Cretaceous to Paleocene San Francisco Formation which, near the bottom of the canyon, are overlain with angular discordance by the Castaic Formation. Southwest of the view location and across Interstate 5 is an elongate ridge underlain by the Violin Breccia and the San Gabriel fault.

Ridge Basin is a northwest plunging asymmetric synclinorium along the east side of San Gabriel fault (Fig. 12A). Extensive research on the basin (Crowell, 1975b; Crowell and Link, 1982; and Link 1987) has shown that the basin formed from 12-8 Ma during large scale right-lateral slip on the San Gabriel fault, an early strand of the San Andreas fault (Fig. 12B). These workers believe the basin fill was laid down, shingle-like, from south to north as a result of movement along the San Gabriel fault (Fig. 12C). The total stratigraphic thickness of the basin (13.5 km) was never present at any one location which is consistent with maturity data (Fig. 12D). To explain the filling of the Ridge Basin Crowell (1982) postulated a conveyor-belt mechanism where the depocenter migrates northward remaining adjacent to a source area across the San Gabriel fault (Fig. 12C middle and upper). This model fails to explain the shingle nature of the bulk of the Ridge Basin deposits which were not derived from across the San Gabriel fault. The shingle-like nature of the Ridge Basin strata resembles stratal arrangements commonly observed above active structures (Suppe and others, 1992). A seismic line across the northern portion of the San Gabriel fault shows it to have a listric shape and dip under the Ridge Basin (May et al., 1993). If the listric-shaped fault surface has a north plunge under the Ridge Basin, right-slip would produce a shingle-like pattern of growth strata in the overlying basin regardless of the position of the source area (Fig. 12C lower).
Figure 12A. Generalized geologic map of the Ridge Basin (modified from Crowell, 1982; Crowell et al., 1982). Abbreviations: bc=undifferentiated crystalline rocks, TKsf=San Francisquito Fm, Tm=Modelo Fm, Tc=Castaic Fm, Tpv=Peace Valley Fm, Trr=Ridge Route Fm, Thv=Hungry Valley Fm. B. Model showing the origin of the Ridge Basin as a releasing bend in the San Andreas fault system (Crowell, 1982). C. Diagrammatic sections along the trough of the Ridge basin showing the shingle-like arrangement of sedimentary units deposited during right strike-slip on the San Gabriel fault (modified from Crowell, 1982). See text for explanation of models. D. Stratigraphic column of the Ridge Basin Group showing mean vitrinite reflectance (Ro) values for 4c samples (Link and Smith, 1982). Samples are from Mobil and Conoco labs. Ro values imply the maximum burial was 2.1 to 3.5 km depth which is consistent with Crowell’s model shown in Fig 12C.
From a petroleum standpoint, the Ridge Basin is anomalous. It is surrounded by richly-productive Neogene basins to the north, west, and south, yet the Ridge Basin itself is not productive. As Link and Smith (1988) have shown, the lack of production may result from poor quality source rock and immaturity. HI and TOC measurements on samples distributed throughout the basin (Fig. 12E) average about 150 mgHC/g rock and 1%, respectively. Vitritine reflectance data mostly range from 0.4%-0.8, showing that the section is immature (Fig. 12D). Why is high-quality source rock not present in this basin? The basin has a number of characteristics associated with rich lacustrine source rocks: tectonic ponding, significant basin duration (approximately 7 Ma), and thick lacustrine shale deposition. A contributing factor may have been climate. The Ridge Basin's climate was probably temperate, whereas a tropical climate promotes rich lacustrine source rock development (Katz, 1990). In a more temperate climate, seasonal overturn allows yearly oxygenation of bottom waters, disrupting the anoxic conditions helpful to kerogen preservation.

Continue north on Interstate 5 along the trough of the Ridge Basin. The Interstate is built along the San Andreas fault zone at the town of Gorman and a number of tectonic geomorphic features occur here such as sag ponds, offset gullies and pressure ridges. North of Tejon Pass the Interstate crosses the Garlock fault, a major left strike-slip fault of southern California. Interstate 5 is along Grapevine Canyon which descends steeply into the San Joaquin Valley and divides the San Emigdio Mountains on the west from the Tehachapi Mountains on the east (Fig. 13A). The mountains are being rapidly uplifted above the San Joaquin Valley and headward erosion of drainageways such as Grapevine Canyon are capturing the gentler-sloped intermontane drainage network. At the front of the range Interstate 5 crosses faults scarps along the Pleito thrust. The thrust places Eocene, Oligocene and Miocene age strata over the Quaternary alluvial units of the valley. Throughout the San Emigdio Mountains the Eocene rocks, which are in the hanging wall of the Pleito thrust system, lie unconformably on the crystalline basement with no evidence of fault detachment. In southern California there seems to be few examples of fault detachment of the sedimentary cover from crystalline basement.

San Emigdio Mountains Summary

The San Emigdio Mountains are a late Pliocene and Quaternary age fold and thrust mountain range along the Pleito thrust system (Fig. 13A). Recorded in the San Emigdio Mountains are older tectonic events that have played an important role in development of the southern San Joaquin basin and other southern California basins. In addition surface exposures, abundant well data, and the proximity of the San Andreas fault make the San Emigdio Mountains an excellent site for the construction of cross sections and the study of transpression.

Figure 13B is a cross section across the San Emigdio Mountains which shows 11.5 km of structural relief on the top of the crystalline basement between the crest of the San Emigdio Mountains and the floor of the San Joaquin basin. Restoration of the cross section to late Pliocene time (Fig. 13C) show that only about 2-3 km of this relief is due to the late Pliocene and Quaternary convergence and about 8-9 km of relief developed between middle Eocene and early Pliocene.

Within the San Emigdio Mountains are several structural and stratigraphic indicators of 2-3 km of uplift during latest Eocene and Oligocene time: 1) The Pleito Formation contains submarine slides or debris flow deposits (seismites of Fig. 14A; DeCelles, 1986). 2) The coarse-grained non-marine Tecuya Formation is the result of nearby uplift. 3) The Caballo Canyon thrust fault placed crystalline basement over sedimentary rocks while an angular unconformity formed in the hanging wall (shown only in Figs. 3A,B). Convergent uplift is believed to be part of the Ynezian orogeny which separates the older expansive forearc basin setting from the younger and more restricted late Cenozoic basins (Fig. 14A).

Throughout the San Emigdio Mountains is a complex set of late Oligocene to early Miocene extensional faults related to the early phase of basin formation. These faults are overlapped by deep-marine strata of middle to late Miocene age deposited during regional subsidence. Middle Miocene to lower Pliocene strata are 3-4 km thicker along the downthrown side of the White Wolf fault than equivalent strata in the higher block suggesting the fault was a north-dipping normal fault separating two subsiding blocks: a rapidly subsiding north block and a slower subsiding south block. Well control shows that the White Wolf fault now dips steeply to the south. We believe the fault was folded into a reverse fault during late Pliocene and Quaternary shortening.

Most of the surface anticlines have formed during late Pliocene and Quaternary convergence and appear to be fault-propagation folds as they are asymmetric to the north and well and surface data show the anticlines lie along thrust ramps that dip less than 25° to the south. Recent uplift of the San Emigdio Mountains has exposed the southern end of the San Joaquin basin (Fig. 14A) and the east-west orientation of the range provides a unique stratigraphic cross section that assists the structural interpretation (Fig. 14B). Upper Eocene and lower Oligocene clastic rocks grade westward from shallow-marine to deep-marine facies and isopach and facies maps of these rocks across the Pleito thrust show little or no lateral offset (Fig. 14C). Keep in mind the San Andreas fault is never more than 10 km to the south of the Pleito thrust. Similarly small earthquakes have mostly compressive focal solutions (Webb and Kanamori, 1985).
Figure 13A. Geologic map of the San Emigdio Mountains (modified from Dibblee and Nilsen, 1973). B. Cross section across the San Emigdio Mountains showing fold and thrust interpretation of late Pliocene and Quaternary convergence. Fault abbreviations: PTS=Pleito thrust system, SAF=San Andreas fault, TT=Tejon thrust, WRT=Wheeler Ridge thrust, WWF=White Wolf fault. Geologic unit abbreviations same as in Fig. 13A. SGC=Santiago Creek, SEC=San Emigdio Creek, STC=Salt Creek. C. Line-length restoration of late Pliocene through Quaternary compressive structures along cross section. Comparison between deformed and restored sections yields 19.2 km of convergence since late Pliocene time (~3 Ma) or 6.4 mm/yr. Restoration shows thrust belt has deformed several small horsts and grabens and the White Wolf normal fault.
Figure 14A. Generalized stratigraphic column of the southern San Joaquin basin and western San Emigdio Mountains showing paleobathymetry and important geologic events (Lagoe, unpublished). B. Stratigraphic framework for Cenozoic rocks of the San Emigdio area (Lagoe, 1987). Relationships are generalized from several east-west oriented transects. Lithologic symbols: 1-bathyal sandstone and mudstone, 2-neritic sandstone and mudstone, 3-non-marine rocks, 5-"seismites" of DeCelles (1986). C. Isopach map of the Metralla Sandstone Member of the Tejon Formation in the upper and lower plate of the Pleito thrust indicating little or no strike-slip since the Eocene (Lagoe, 1987). Horizontal line pattern shows depocenter and contours are in feet.
The close proximity of the San Andreas fault presented an interesting problem during restoration of the deformed upper plate of the Pleistocene thrust system. The San Andreas fault can either be offset by the Pleistocene thrust or the thrust can steepen into the San Andreas fault as a mega-flower structure. Restoration of originally flat-lying strata along a steepening with depth fault creates more problems than it solves, and the lack of strike-slip deformation north of the San Andreas fault does not allow for explanations away from the line of section. We have chosen to offset the San Andreas fault in our interpretation.

**Stop #4, Southern San Joaquin Basin and Wheeler Ridge Oil Field**

This stop is along the northern edge of the Wheeler Ridge oil field near the California Aqueduct crossing of the ridge (Fig. 13A). Here the ridge is underlain by steeply-dipping beds of the Tulare Formation as a non-marine unit of Quaternary age. Wheeler Ridge anticline lies along the range front of the San Emigdio Mountains and just south of the deepest part of the San Joaquin basin (Fig. 15A). The narrow canyon to the south that crosses Wheeler Ridge is a wind gap formed by the rapid uplift of the anticline during the late Pleistocene and deflection of the north-flowing drainage around the eastern nose of the anticline.

Well data show the anticline is underlain by the Wheeler Ridge thrust which dips to the south and ramps across the Oligocene and Miocene section (Fig. 15B). The thrust displaces Oligo-Miocene age normal faults, and several of the oil producing horizons, and is a bedding plane fault in the lower part of Oligocene section. Structural interpretations of the Wheeler Ridge anticline vary. Medwedeff (1989) working on the eastern end of the anticline interpreted the north limb of the fold as a structural wedge driven northward into the flat-lying strata of the San Joaquin basin. In this interpretation Wheeler Ridge anticline is a fault-bend fold connected to a shallow north-dipping backthrust. Alternatively in Figure 15B we interpret the Wheeler Ridge anticline to be a fault-propagation fold because of its asymmetric profile, steep north limb, extreme decrease in fault slip upsection, lack of surface exposure, and lack of an upper thrust flat beneath the north limb of the anticline.

Deep drilling shows the Wheeler Ridge anticline lies structurally above the broader Tejon anticline. The White Wolf fault, now a south-dipping reverse fault, cuts the north limbs of the Wheeler Ridge and Tejon anticlines. The White Wolf fault is the boundary between the thick basin fill of the Tejon depocenter and a thinner and coeval section under the Tejon embayment.

Carbon isotope data suggests that the Wheeler Ridge field oils were generated from the Monterey Formation (Fig. 9A), although the organic richness of the underlying Temblor Formation allow the possibility that it may have contributed. Burial history modeling implies that south of the White Wolf fault the entire sedimentary section is immature for hydrocarbon generation (Figs. 16A and B). Heat flow in the area is very low, ranging from 1.0-1.2 HFU making oil and gas generation exceptionally deep. Thermal modeling and maturity data from deep wells north of the White Wolf fault, corroborated by biomarker data on Wheeler Ridge oils, show that oil and gas are being generated at depths of 4.9-6.1 km and 6.1-7.3 km, respectively (Figs. 17A-D and 18A); only the lower Monterey and Temblor Formations are at oil generation depths. The gas found at Wheeler Ridge may originate from more deeply buried Temblor Formation or older units.

Modeling also shows that oil generation is active and began 2-4 Ma, or before anticlinal folding at Wheeler Ridge. A significant volume of oil may have been lost before a trap developed, or oil was trapped in earlier extensional or smaller-amplitude anticlinal traps and remigrated during the Quaternary deformation. Later in the trip we will stop at the Cuyama basin where oil is trapped in Miocene age structures, and at South Mountain oil field in the Ventura basin where older trapping is also a possibility. Remigration may be a common phenomenon in southern California even though petroleum generation is very young because: 1) In the deepest parts of the basin oil generation can pre-date the youngest anticlines. 2) Many of the young anticlines are localized along older basin-edge faults (Fig. 2A) where petroleum traps may have already existed.

Total oil discovered in the southeastern portion of the San Joaquin basin is small compared to that of the western San Joaquin and Bakersfield arch areas. This may result from the Monterey Formation not fully reaching maturity or the small down-dip fetch area north of the White Wolf fault (Fig. 15A).
Figure 15A. Structure contour and oil field map of the southeastern San Joaquin basin (Webb, 1977 and DOG, 1985). Contours on N point-a near top of Monterey Formation equivalent; 610 m (2,000 ft) contour interval. Abbreviations: BA=Bakersfield arch, TE=Tejon embayment, TD=Tejon depocenter, WWF=White Wolf fault. B. Cross section across Wheeler Ridge oil field and southern end of the Tejon depocenter.
Figure 16A. Wheeler Ridge field area burial history showing % Ro. Heatflow = 0.8 HFU. Sun Wildflower #48x-2 well.

Figure 16B. Wheeler Ridge field area modelled and actual maturity. Sun Wildflower #48x-2 well. Maturity data courtesy of CoreLab.
Figure 17A. Tejon kitchen burial history showing HC transformation ratio (%). Heat flow = 1.13 HFU. Superior Sand Hills #64x-34 well.

Figure 17B. Tejon kitchen modelled and actual maturity. Maturity data courtesy of CoreLab.

Figure 17C. Tejon kitchen generation rates versus time. Calculated generation rates assume Tt is oil source rock similar to Tm.

Figure 17D. Tejon kitchen generation rates versus depth. Calculated genertion rates assume Tt is oil source rock similar to Tm.
Figure 18A. Yowlumne field burial history showing HC transformation ratio (%). Texaco San Emidio #1 well. Incorporates maturity data courtesy of CoreLab.

Figure 18B. Maturity of California oils including Yowlumne, Wheeler Ridge and South Mountain. Courtesy of Albert Holba, ARCO Exploration and Production Technology Company.
Figure 19A. Structure contour map on the Main zone, or F2 zone, at the Wheeler Ridge oil field. B. Cross section of Wheeler Ridge oil field showing multiple producing horizons and trap styles. C. Generalized stratigraphic section for the Wheeler Ridge oil field and the Tejon embayment showing producing horizons.
Summary of Wheeler Ridge Oil Field
Tom Butler
Vintage Petroleum, Inc.
Tulsa, OK

Wheeler Ridge oil field is trapped by Quaternary anticlinal folding along the range front of the San Emigdio Mountains. The anticline is asymmetric with a steep north limb (Fig. 19A). The simple surface anticline masks a complex oil field with five major pools and ten separate oil producing horizons discovered over a 70 year span (Figs. 19A-C). The cumulative production for the field is estimated to be 50 MMBO and 100 BCFG. The principal trapping mechanism is anticlinal but fault and stratigraphic traps play an important role in some of the pools (Fig. 19B). Standard Oil Company completed the first producing well from the crest of the anticline in the Main or F2 zone of the Monterey Formation in 1922. In 1947 Richfield Oil Company (now ARCO) discovered the Coal Oil Canyon Pool at the west end of Wheeler Ridge anticline. In the subsequent decade Richfield made additional discoveries with the Valv and Olosee Pool, the Vedder Pool, the Oligocene Pool and the Eocene Pool. Cross sections using surface and subsurface data defined the asymmetry of the Wheeler Ridge anticline which led to deeper drilling along the south limb of the anticline during the late 1930's. This drilling led to the discovery of the Wheeler Ridge thrust fault, and subsequent exploration of the footwall led to the discovery of the Vedder and Eocene pools. As recently as 1989 ARCO added an Oligocene Vedder gas/condensate pool to the field.

The reservoir sands were deposited in a variety of sedimentary environments ranging from fluvial to deep water and have 15 to 25% porosity with productive thicknesses from 6 to 60 m. Oil gravities range from 20° API in the shallower zones to 43° API in the deeper zones. Potential sources for the oil and gas are the Monterey, Temblor and Tejon Formations although the Monterey Formation is considered the most likely source unit. Recovery from the Wheeler Ridge oil field has been a result of solution gas drive, gravity drainage, gas injection, water influx, waterflood, steamflood and fireflood. There are a total of 47 active and 110 shut-in producing wells with 6 active and 32 shut-in water injection wells. During December 1995 the field produced an average of 389 BOPD, 389 MCFD, and 1342 BWPD.

Wheeler Ridge oil field still offers plenty of opportunities with its complex geology, multiple pay zones and trap styles, and potential for pre-Monterey Formation source beds. Through extension wells, infill drilling, recompletions, secondary and tertiary recovery operations, Wheeler Ridge oil field appears to have the potential for significant reserve additions into the next century.

Exit Wheeler Ridge oil field via the Wheeler Ridge Pump Station Road and turn left (west) on to Highway 166. Highway passes over a number of oil fields at the southern end of the San Joaquin basin (Fig. 15A). Combination structural-stratigraphic traps are the principal style with east-plunging anticlines and northwestward trending submarine fan lobes and channels (Webb, 1977). To the south the range front of the San Emigdio Mountains is very young with upper Pleistocene gravel tilted up to 60°. Continue west on Highway 166 to the town of Maricopa and the southern end of the giant Midway Sunset oil field (Figs. 20A-B). Turn right (north) on to Highway 33 and continue several miles to the City of Taft. Turn left on to Lincoln Street and continue to the Fill 25 area of the Midway Sunset oil field.

Stop #5, West side of the San Joaquin Basin, Temblor Range and Midway Sunset Oil Field.

The stop is on the crest of Hill 25 which is the surface expression of the Spellacy anticline, one of several plunging anticlines within the Midway Sunset oil field (2,750 MMBO and 589 BCF EUR). Currently the most important producing interval in this area is the Monarch sandstone which proclives from both flanks of the Spellacy anticline, the northeast flank of Thirty Five anticline, and the Spellacy syncline. The valley to the south is the surface expression of the Spellacy syncline which separates the Spellacy and Thirty-Five anticlines. Evidence of on-going thermal operations can be seen in many places. Midway Sunset field is the largest of eight giant oil fields located on the west side of the San Joaquin basin (Fig. 20A). To the northeast, beyond the City of Taft, are two giant oil fields: Buena Vista anticline (676 MMBO and 1.2 TCF EUR) and behind is Elk Hills anticline (1,531 MMBO and 1.9 TCF EUR).

To the west is the southern Temblor Range which is underlain by a set of northwest-trending anticlines (Fig. 20B). Harding (1976) interprets these anticlines to be the result of wrench tectonics along the San Andreas fault, which is located about 15 km to the west, while Namson and Davis (1988a) interpret these anticlines as part of the Coast Range fold and thrust belt. The Temblor Range is being uplifted by these anticlines which are underlain by thrusts faults known from deep drilling (Figs. 21A-B).

The southern Temblor Range is notable for significant late Miocene folding and thrusting and synorogenic deposition (Fig. 21C, Santa Margarita event). Along the crest of the range breccia, conglomerate and sandstone of the Santa Margarita Formation lie with angular discordance on folds and thrust faults (Fig. 20B). The Santa Margarita Formation was derived from the west and across the San Andreas fault and distinctive basement clasts within the formation indicate a source in the northern Gabilan Range now right laterally offset 240 km (Huffman, 1972).
Figure 20A. Structure contour and oil field map of the southwestern San Joaquin basin (Webb, 1977 and DOG, 1985). Contours on N point (a near top of Monterey Formation equivalent); 610 m (2000 ft) contour interval.

Figure 20B. Surface geologic map of the southern Temblor Range and southwestern San Joaquin basin (modified from Dibbee, 1973). Abbreviations: KJd=undifferentiated Coast Range Ophiolite and Franciscan Assemblage, TKd=undifferentiated lower Tertiary strata and possibly Cretaceous strata, Tt=Temblor Fm, Tm=Monterey Fm, Tsm=Santa Margarita Fm, Tbw=Bitterwater Shale, Tuc=unnamed Pliocene strata, Trt=Reef Ridge Shale, Te=Etchegoin Fm, Tsj=San Joaquin Fm, QTt=Tulare Fm.
Figure 21A. Cross section across the southern Temblor Range and southwestern San Joaquin basin. B. Cross section restoration which yields 9.0 km of convergence during the last 7.0 Ma or 1.3 mm/yr-includes Santa Margarita and Pasadenaan convergent events. Uplift and folding in mountain range is interpreted to result from thrust ramps in the Gonyer thrust system (GTS) and Midway Peak thrust fault (MPF). Deeper basement-cored anticlines at Buena Vista and Elk Hills remain unexplained. Other abbreviations: RPF=Recruit Pass fault, SAF=San Andreas fault and in Fig. 20B.

Eocene age source rock may have generated oil as early as late Miocene in the southern Temblor Range. The range is underlain by a very thick section (at least 4.3 km) of Oligocene and Miocene age deep-marine deposits (Fig. 21A). To the north the Eocene age Kreyenhagan Formation has hydrocarbon source potential and is a principal source for oil north of the southern San Joaquin basin (Graham, 1987; Peters and others, 1994).

Figure 21C. Generalized stratigraphic column of the southern Temblor Range (Lagoe, unpublished).
Figure 22A. Diagrammatic longitudinal cross section showing relationship of principal Miocene age producing sandstone units. B. Diagrammatic cross section across Midway Sunset, Buena Vista, and Elk Hills oil field showing trap styles.

Midway Sunset Oil Field
Mike Simmons
ARCO Western Energy Company
Bakersfield, CA

Since discovery of the Midway Sunset oil field, some time in the early 1890's, production has been established from upper Miocene, Pliocene, and Pleistocene sandstone, fractured shale, and diatomite of bathyal marine to continental origin. The field is an amalgamation of many individual pools encompassing an area of over 200 km² (Fig. 20A). The pools result from many types of traps but the most significant ones are associated with the Mio-Pliocene unconformity as the result of truncation of Miocene reservoirs and the pinchout of onlapping Pliocene reservoirs. To date the field has produced approximately 2,300 MMBO of primarily heavy crude, generally from depths of less than 1500 m. As the result of application of steam technology beginning in the 1960's, the field has set 18 annual production records since 1972, and currently produces over 160,000 BOPD, placing it third behind Prudhoe Bay and Kuparuk in terms of daily production for domestic fields. Official remaining reserves for the field stand at 450 MMBO.

The structure at the top of the Monterey Formation (Fig. 20A), locally known as the Antelope Shale, is a relatively simple northeast-dipping homocline modified by a series of en echelon, southeast-plunging anticlinal noses. Detailed knowledge of the stratigraphy within the field area only exists for the major producing units: the Antelope Shale and younger Reef Ridge, Etchegoin, San Joaquin, and Tulare Formations. These units document the progressive filling of an intraslope basin, initially by Miocene deep-marine submarine-fan deposits, and shallow-marine fan-deltas, then Pliocene nearshore marine deposits, later still by Pliocene brackish and freshwater sediments, and finally by Pleistocene alluvial fan deposits. The complex distribution pattern of many Miocene sandstone reservoirs was strongly influenced by syndepositional tectonic activity and northerly translation of the granitic Salinian block source area, associated with the evolution of the San Andreas fault (Huffman, 1972). This has resulted in numerous interpretations of the internal stratigraphy of the Miocene section, one of which is presented here as Figure 22A. The combination of structure and stratigraphy results in trapping geometry’s illustrated in the regional cross section shown in Figure 22 B, which extends across three giant oil fields: Elk Hills, Buena Vista, and Midway Sunset. The section depicts small anticlinal closures and major truncations of the Miocene reservoirs, the pinchouts of onlapping Pliocene reservoirs, and the unconformable juxtaposition of continental Pleistocene reservoirs with the Miocene section which is also the source of the oil.
Leave stop via the City of Taft and take Highway 119 across the Bunea Vista and Elk Hills oil fields (Fig. 20B) paralleling the cross section shown in Figure 21 A. For additional reading on the San Joaquin basin see Graham (1988), Kuespert and Reid (1990) and Callaway and Rennie (1991). Continue east on Highway 119 to Highway 99 and go north to the City of Bakersfield for the evenings lodging.

ROAD LOG (SECOND DAY)

Depart Bakersfield in the morning and take Highway 99 south to Highway 119 and go west to Old River Road. Go left on Old River Road south across the north side of the Tejon depocenter (Fig. 15A). Turn west on to Highway 166 and continue through Maricopa. Highway 166 climbs west through the southern Temblor Range to the San Andreas fault (Fig. 20A). Turn left on to the Soda Lake Road and continue several miles north until the southern Carrizo Plain and Caliente Range are visible to the northwest.

Stop #6, The San Andreas Fault

The active trace of the San Andreas fault is just east and parallel to the Soda Lake Road. The San Andreas fault is the plate boundary between the North American and the Pacific plates and the fault cuts obliquely across the Coast Range and Transverse Ranges fold and thrust belt. Offset geologic features indicate a significant right strike-slip has occurred on

Figure 23. Aerial photograph of the San Andreas fault, southeastern Caliente Range, and Elkhorn Hills. Arrows point to active trace of fault with tectonic landforms such as right-offset gullies, pressures ridges and sag ponds.
Figure 24A. Regional cross section from the San Andreas fault to Coal Oil Point (Santa Barbara Channel). Cross section restoration which yields 57.3 km of convergence during the last 2.0-3.0 Ma or 19.1-28.7 mm/yr. Fault abbreviations: COPT=Coal Oil Point thrust; SCTS=San Cayetano thrust system; SYF=Santa Ynez fault; CF=Camuesa fault; LPF=Little Pine thrust; PSLT=Point San Luis thrust; BPF=Big Pine fault; BPTS=Big Pine thrust system; RNF=Rinconada-Nacimiento fault; SCF=South Cuyama fault; BMT=Black Mountain fault; MT=Morales thrust; WRT=Wells ranch thrust; SAF=San Andreas fault; CBF=Cuyama Basin fault; MTS=Morales thrust system. Geologic unit abbreviations: PCh=Precambrian and possibly younger high-temperature metamorphic rocks; Mzr=Mesozoic plutonic rocks; Ksf=Franciscan Assemblage and possibly Coast Range ophiolite equivalent; Ku=undifferentiated Cretaceous strata-includes Jalama Formation and various unnamed units; TKu=undifferentiated and unnamed lower Tertiary and Upper Cretaceous strata of Sierra Madre and Cuyama basin; Te=undifferentiated Coldwater, Cozy Dell, Junca, and Maltijaha Formations; Tsi=Simmiller Formation; Tsp=Sespe Formation; Tv=Vaqueros Formation; Tmo=undifferentiated lower Miocene and Oligocene strata; Tr=Rincon Formation; Tm=Monterey Formation; Tc=Caliente Formation; Tsm=Santa Margarita Formation; Tsg=Sisquoc Formation; Tq=Quatal Formation; Tmr=Morales Formation; Qpr=Paso Robles Formation; QPu=undifferentiated Pico, Santa Barbara, and Saugus Formations, and unnamed upper Quaternary alluvial units.

Figure 24C-D. Kinematic model showing the interaction between concurrent thrust faults and strike-slip faults across the North American/Pacific plate boundary (Namson and Davis, 1988a). See text for discussion of model.
the fault during the last 2-3 Ma contemporaneous with
development of the fold belt. Aerial photographs of
the San Andreas fault in Carrizo Plain are common in
many geologic textbooks. Figure 23A is an aerial
photograph showing the portion of the San Andreas
fault zone we are visiting. Clearly visible are many of
the tectonic geomorphic features common to a large
strike-slip fault such as offset gullies, pressure ridges
and sag ponds. The last earthquake to rupture this
segment of the fault occurred in 1857 (Fort Tejon
earthquake, M=8.0). To the southwest of the stop is
the Caliente Range underlain by strata of the Cuyama
basin and to the east of the stop are Elkhorn Hills and
the southern Temblor Range which are underlain by
strata of the San Joaquin basin.

The aerial photograph shows some other
noteworthy aspects of the San Andreas fault that are
important to the debate over the structural style of
transpression. The fault does not occur along a range
front; for instance the Caliente Range has been uplifted
along the northeast-dipping Morales thrust. Well and
seismic reflection data indicate the Morales thrust has a
dip of about 20° under the range and little or no
strike-slip offset (Davis and others, 1988). We believe
the Morales thrust has a shallow dip under the Carrizo
Plain and intersects and displaces the San Andreas fault
(Figs. 24A-B). At first glance this seems unusual but
steepening of the Morales thrust into the San Andreas
fault creates several problems: 1) Hanging wall strata
of the Morales thrust would not restore to horizontal
layers but rather a wedge of steeply-dipping strata.
One is then required to explain the cause of this earlier
deformation. 2) Recent hanging-wall uplift along a
steep Morales fault would have created a mountain
range where there is the Carrizo Plain. 3) The lack of
strike-slip movement along the Morales thrust
suggests it does not merge with the San Andreas fault
(Davis and others, 1988).

Displacement of the San Andreas fault by the
Morales fault fits into a more regional model we have
proposed (Namson and Davis, 1988a). Strain
associated with the convergent strike-slip motion
between the North American and Pacific plates is
resolved into tangential and normal components with
respect to the San Andreas fault. In the upper crust
(above the brittle-ductile transition), the tangential
component is primarily strike-slip motion along the
San Andreas fault, whereas the normal strain
component is manifested as thrust faults and folds in
the Coast Ranges and Transverse Ranges that generally
have trends parallel to the San Andreas fault. The
proposed kinematics are illustrated in Figures 24C-D,
which shows thrust faults flattening into the brittle-
ductile transition while the San Andreas fault continues
into the lower crust. As crustal convergence occurs,
points A and B can remain a constant distance from the
San Andreas fault, whereas points C, D, E, and F
move toward the San Andreas fault with plate
convergence, motion on the thrusts, and over-all
lithospheric shortening. The fold belt propagates
westward into the offshore west of the San Andreas
fault and eastward into the San Joaquin Valley east of
the San Andreas fault even though the net motion of
material points within the fold belt is toward the San
Andreas fault. The lower crust and lithosphere are
shortened an amount equivalent to that in the shallow
crust by either tectonic thickening or incipient
subduction into the athenosphere.

Return to Highway 166 via the Soda Lake Road.
Continue west on Highway 166 past the intersection
with Highway 33 and into the Cuyama basin (Fig.
25A). The highway parallels the trough of the
present-day Cuyama basin. On the right (north) is the
Caliente Range with the north-dipping Morales thrust
at the base of the range front (Fig. 25B). Visible on
the flank of the Caliente Range is the eastward
transition from marine to non-marine strata of
Miocene age. Well data from the Cuyama Valley show
this transition is not laterally offset by the Morales
thrust (Davis and others, 1988). Pass through the
small towns of Cuyama and New Cuyama. The high
mountain to the right and across the valley is Caliente
Mountain and most of the strata visible belong to the
Painted Rock Sandstone Member of the Vaqueros
Formation with the Soda Lake Shale Member exposed
in the core of the Caliente Mountain anticline. This
thick section has been thrust southward over a coeval
but much thinner section by the Morales thrust system
(Fig. 25B). Drilling and other exploration activities
by ARCO in the early 1980's proved a subthrust basin
lies beneath Caliente Mountain (Figs. 25A, 26B). This
subthrust basin contains the principal source and
reservoir beds of the Cuyama basin; however, the
hydrocarbon potential of this subthrust basin remains
largely untested. At Russell Ranch oil field turn right
off highway and park near small hill south of the
Cuyama River.

Stop #7, Cuyama Basin and Russell Ranch Oil
Field

Stop is just north of Highway 166 and south of
the Cuyama River (Fig. 25A). North of the Cuyama
River is Whiterock Bluff with the Caliente Mountain
in the background to the right. Whiterock Bluff
exposes siliceous shale of the Monterey Formation
thrust over the Morales Formation by the Whiterock
thrust. The Whiterock thrust, which lies structurally
below the Morales thrust, can be seen along the
mountain front northwest (left) of Whiterock Bluff.
Along the trace of the fault is a dark conical-shaped
hill underlain by Cretaceous age strata. The hill is
bounded on the right by a normal fault and on the left
by the north-dipping Whiterock thrust. This fault
block is the result of the younger thrust ramping up
and cutting across the older normal fault.
Figure 25A. Surface geologic map of the Cuyama Basin (modified from Dibblee, 1973; Davis et al., 1988). Abbreviations for map and cross section (Fig. 25B): KIf=Franciscan Assemblage, Mzgr=Mesozoic granitic rocks—may include some Precambrian gneissic rocks, TKu=Upper Cretaceous and lower Tertiary strata, Tsi=Simmler Formation, Tv=undivided Vaqueros Fm (Tvq=Quail Canyon Mbr, TvI=Soda Lake Shale Mbr, Tvp=Painted Rock Sandstone Mbr), Tm=undivided Monterey Fm (Tma=Saltos Shale Mbr, Tmw=Whitterock Bluff Shale Mbr), Tb=Basalt dikes, flows and sills, Tbc=Branch Canyon Sandstone, Tc=Caliente Fm, Tsm=Santa Margarita Fm, Tq=Quatal Fm, Tmo=Moraes Fm, QTU=Paso Robles Fm?, Qoa=older alluvium, Qa=alluvium.

Figure 25B. Cross section across the Caliente Range showing basin inversion along Morales thrust (MT). The thickest portion of the Cuyama basin is thrust over thinner stratigraphically equivalent units of the Cuyama shelf. The Morales thrust ramps up above an older basin-bounding-normal fault. The presence of the subthrust basin was suggested by balanced cross sections and proven by drilling and seismic reflection data (Davis et al., 1988). Caliente Mtn. anticline is shown as a displaced fault-propagation fold. RNF=Rinconada fault, units abbreviations same as Fig. 25A.
Oil was first discovered in the Cuyama basin at the Russell Ranch field (EUR 69 MMBO, 50 BCFG) in 1948. The following year South Cuyama field was discovered (EUR 216 MMBO, 225 BCFG), and in the following several years three small discoveries were made in the Cuyama basin. Since South Cuyama's discovery, no larger field has been discovered in onshore California. The Cuyama oil is sweet, high-gravity crude, ranging from 25° to 40° API. Most of the production is from the Painted Rock Sandstone, (Dibblee sand) which has porosity's reaching 28% and permeability's up to 800 md. The oil accumulation at South Cuyama has a large gas cap comprising almost half of the hydrocarbon pore volume.

Russell Ranch oil field is a faulted anticlinal trap (Fig. 27) as is South Cuyama oil field. The bounding faults on the southwest side of the fields and the numerous faults within the fields have normal separation. Both the Monterey Formation and Soda Lake Shale Member of the Vaqueros Formation are potential source units. Both are organically rich (TOC>3%) and contain sapropelic kerogen; however because of maturation considerations we feel that the Soda Lake Shale is the primary source for the Cuyama oils.

The Cuyama basin petroleum system is different from typical southern California system in two significant ways: 1) Oil is not sourced from the Monterey Formation but from the older Soda Lake Shale (Fig. 26A). 2) Oil generation pre-dates late Pliocene and Quaternary crustal shortening, whereas in the Monterey Formation-sourced basins much of the generation and migration are coeval with young crustal convergence. Cuyama's oil fields have traps resulting from Miocene extension and a local phase of late Miocene convergence. The large late Pliocene and Quaternary convergent structures such as the Caliente Mountain anticline are dry in contrast to similar age anticlines in other southern California basins.

Carbon isotope data (Fig. 9A; Lundell and Gordon, 1988), source rock data, and burial history modeling show that while the Monterey Formation is a very rich source rock in the Cuyama basin it is immature. In contrast, Soda Lake Shale organic facies are variable (Lundell and Gordon, 1988). In some places source rock quality is excellent, with TOCs approaching 4% and HIs above 400, but in other areas it is poor. These source facies variations reflect sedimentary facies variation controlled by syndepositional extension. Pre-thrusting reconstruction shows that the best source rocks are
located in the deepest parts of the basin which are located 15-20 km to the northeast of the oil fields (Fig 26B). This depocenter formed in Oligocene and Miocene time and burial history modeling strongly suggests that the Soda Lake Shale became mature in the depocenter during late Miocene and Pliocene time (Figs. 28A, 28D; Lundell and Gordon, 1988; Lillie, 1994). Some of the oil and gas may have migrated into Cuyama’s oil fields at that time. Alternatively, it is possible that some of the petroleum originally trapped in extensional structures in the depocenter was remigrated into these fields during late thrust-related northeasterly tilting of the basin. See Bazeley (1988) for additional reading on the Cuyama basin.

Return to Highway 166 and go east and back through towns of New Cuyama and Cuyama. Turn right onto Highway 33 which parallels the trough of the eastern Cuyama basin. Here the basin is largely non-marine consisting of a thick sequence of alluvial fan, fluvial and lacustrine deposits of Miocene and Pliocene age. On the right is the Sierra Madre which is being uplifted by the southwest-dipping Ozena fault (Fig. 29A). Cross into the hanging wall of the Ozena fault and pass the Lockwood Valley Road and the Ozena Ranger Station. Highway 33 climbs the north side of the Sierra Madre which are underlain by +10 km thick elastic section of upper Cretaceous through Eocene rocks. About half way up mountain front the
Figure 28A. Cuyama kitchen burial history showing HC transformation ratio (%). Arco Stone #1 well and surface geology composite. Heat flow = 1.53 HFU.

Figure 28B. Cuyama basin paleostructure of base Miocene at end Pliocene time, just before thrusting. Normal faults have blocks on downthrown side; future thrust has barbs on upthrown side.

Figure 28C. Cuyama kitchen modelled and actual maturity. Arco Stone #1 well.

Figure 28D. Cuyama kitchen Soda Lake generation rates versus time.
Figure 29A. Map showing field trip stops and major surface faults of the central portion of the western Transverse Ranges.

Figure 29B. Regional cross section from Port Hueneme to the Big Pine fault (BPF). C. Cross section restoration which yields 31.4 km of convergence during the last 2.0-3.0 Ma or 10.5-15.7 mm/yr. Fault abbreviations: ORF=Oak Ridge fault; LF=Lion fault; SCT=San Cayetano thrust; SYF=Santa Ynez fault; SCTS=San Cayetano thrust system; SMT=South Mountain thrust; PMF=Pine Mountain thrust; SGLF=San Guillermo fault; BPF=Big Pine fault. Geologic unit abbreviations: pCgn=Precambrian and possibly younger high-temperature metamorphic rocks; Mzgr=Mesozoic plutonic rocks; KJf=Franciscan Assemblage and possibly Coast Range ophiolite equivalent; Ku=undifferentiated Cretaceous strata; Tj=Juncal Formation; Te=undifferentiated Coldwater, Cozy Dell, Llajas, and Matilija Formations; Tsp=Sespe Formation; Tv=Vaqueros Formation; Tr=Rincon Formation; Tm=Modelo and Monterey Formations; Tsq=Sisquoc Formation; Pu=Pico Formation; QFq=undifferentiated Saugus Formation and various unnamed alluvial units.
Figure 29D. Regional cross section from the Santa Monica Mountains to the San Andreas fault (SAF). E. Cross section restoration which yields 33.2 km of convergence during the last 2.0-3.0 Ma or 11.1-16.6 mm/yr. Fault abbreviations: MCF=Malibu Coast fault; EPTS=Elysian Park thrust system; SMT=South Mountain thrust; ORF=Oak Ridge fault; ST=Sisar thrust; BCF=Big Canyon thrust; SYF=Santa Ynez fault; SCTS=San Cayetano thrust system; PMF=Pine Mountain fault; PTS=Plieto thrust system; SCT=San Cayetano thrust; SAF=San Andreas fault. Geologic unit abbreviations: pCgn=Precambrian and possibly younger high temperature metamorphic rocks; Mzgr=Mesozoic age plutonic rocks, Mzcs=Catalina Schist; KJ=Franciscan Assemblage and possibly Coast Range Ophiolite equivalent; Ku=undifferentiated Cretaceous age strata; Te=undifferentiated Coldwater, Cozy Dell, Juncal, Llajas, and Matilija Formations; Tsp=Sespe Formation; Tv=Vaqueros Formation; Tt=Topanga Formation; Tr=Rincon Formation; Tc=Conejo Volcanics; Tm=Modelo and Monterey Formations; Tsq=Sisquoc Formation; Pu=Pico Formation; Qps=undifferentiated Saugus Formation and various unnamed alluvial units.
road crosses the Big Pine fault, a late Cenozoic strike-slip fault that is a major tear fault in the western Transverse Ranges fold and thrust belt. For additional information on the structure and stratigraphy across this portion of the western Transverse Ranges see Davis and Namson (1987).

**Stop #8, Santa Ynez-Topatopa Range, Santa Ynez Fault, and Western Transverse Range Fold and Thrust Belt**

Stop is along the east side of Highway 33 just south of Sespe Creek (Fig. 29A). Outcrops just west of the stop are Matilija Sandstone on the north limb of a large anticline. Prominent sandstone outcrops north of Sespe Creek are Sespe and Coldwater Formations along the trough of an east-plunging syncline. The steeply dipping north limb of the syncline is interpreted as a portion of the lower limb of a fault-propagation fold cut by the Pine Mountain thrust (Fig. 29B). The high ridge behind (north) the syncline is Pine Mountain which is underlain by a thick sequence of Eocene strata in the hanging wall of the Pine Mountain thrust. Our location is between the Neogene age Ventura and Cuyama basins. Older rocks exposed along this portion of Highway 33 are forearc deposits predating the Ynezian orogeny (Fig. 30B).

Continue south on Highway 33 crossing the crest of the Santa Ynez- Topatopa Range, the Santa Ynez fault, and the Matilija overthrust. Enter City of Ojai and turn right at Highway 150. Ojai lies along the highly deformed northern margin of the Ventura basin (Figs. 30A-B). Continue east on Highway 150 through Ojai. Highway climbs on to the Lion Mountain anticline and road cuts are red beds of the Sespe Formation.

**Stop #9, Ojai Valley and Deformed Northern Margin of the Ventura Basin**

Stop is in a large parking area with an excellent overview on the right hand side of Highway 150 southeast of the town of Ojai (Fig. 29A). To the north of the stop and across the Ojai Valley is the Topatopa Range and the Matilija overthrust. The overturned section dips northward with red beds of the Oligocene Sespe Formation nearest the valley floor and outcrops of Eocene Coldwater Formation and older units making the higher ridge. The Matilija overthrust is the easternmost extension of a southward younging homoclone that extends westward from Ojai to Point Conception a distance of about 100 km. To the east of Ojai the overthrust is broken by the San Cayetano thrust which places the Eocene section over the Miocene and Pliocene rocks folded in the Lion Mountain anticline.

Stop is near the crest of the Lion Mountain anticline which lies between the Ventura anticline to the south and the Topatopa Range to the north (Fig. 29B). West of this location and along the crest of the Lion Mountain anticline small amounts of cil have been produced from sandstone of the Coldwater Formation. The Lion Mountain anticline plunges eastward under upper Ojai Valley where oil is produced from fractured shale and thin sandstone beds of the Monterey Formation, and from the unconformity between the Saugus Formation and Monterey Formations. Numerous oil seep occur from fractured shale of the Monterey Formation along Highway 150 just east of upper Ojai Valley.

The high ridge visible to south of the stop is underlain by south-dipping Oligocene and Miocene age rocks. The section is cut by the Lion Mountain fault, a near bedding-plane-parallel fault, near the base of the ridge. The south dipping section is a nearly complete surface section of the Ventura basin exposed along the south limb of the Lion Mountain anticline. The Oligocene through Quaternary section is about 7 km thick with the upper 4 km consisting of Pliocene and Quaternary strata.

Namson (1987) interprets the structure of the Santa Ynez and Topatopa Mountains to be the result of a phase of late Eocene to early Oligocene convergence overprinted by late Pliocene to present convergence. To the north of the stop the Plio-Quaternary deformation is recorded in two stacked anticlines, both cored with Cretaceous and possibly older rocks, and underlain by the splays of the San Cayetano thrust.

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**Figure 31. Model illustrating the late Eocene to Oligocene deformation of the San Rafael Mountains and Santa Ynez fault (Namson 1987).**
system (Fig. 29B). The Santa Ynez fault is interpreted to be an older south-dipping back thrust that was deformed by the San Cayentano thrust system and associated hanging wall folds (Fig. 31).

Continue east on Highway 150 through the upper Ojai Valley (Fig. 30A). To the right is Sulphur Mountain and at its base is the south-dipping Sisar thrust. The Ojai oil fields occur along a small triangle zone between Sisar and San Cayentano thrusts (Fig. 29D). As the road descends into Santa Paula Creek watch for extensive oil seeps from the fractured Monterey Formation outcrops along the right side of the road. Highway 150 parallels the cross section and restoration shown in Figures 29D-E as it passes through the City of Santa Paula. South of the Santa Paula take the South Mountain Road east to the South Mountain oil field road and turn right.

Stop # 10, Central Ventura Basin and South Mountain Oil Field

The South Mountain oil field is trapped along the Oak Ridge fault trend (Fig. 30A). The crest of the South Mountain anticline is well exposed in a large ravine just west of the stop. Folded red beds of the Sespe Formation define a north vergent anticline. The south limb of South Mountain anticline continues under the high ridge to the south which is underlain by south-dipping beds of the Topanga and Monterey Formations. South Mountain anticline is Quaternary in age as its south limb folds the Pliocene Pico and

Figure 30A. Structure contour and oil field map of the western Ventura Basin (modified from Hindle et al., 1991 and DOG, 1974). B. Generalized stratigraphic column of the Ventura Basin (Lagoe, unpublished).
Figure 32A. Cross section A-A’ through the Oak Ridge-Montalvo trend near the Montalvo oil field. B. Cross section B-B’ through the Oak Ridge-Montalvo trend near the South Mountain oil field. C. Cross section C-C’ through the Oak Ridge-Montalvo trend near the Bardsdale area.
Quaternary Saugus Formations into a large syncline south of the stop. Unconformities separate the Monterey and Pico Formations and the Pico and Saugus Formation suggesting multiple phases of folding.

To the north of the oil field is the Santa Clara River valley which is underlain by the east-west trending central portion of the Ventura basin. The deep basin is separated from the Oak Ridge-Montalvo anticlinal trend by the Oak Ridge fault which dips steeply to the south under the anticline. Three cross sections of the Oak Ridge-Montalvo trend and southern portions of the Ventura basin are shown in Figures 32A-C. We are located near the cross section shown in Figure 32B. All three cross sections have structural styles in common which include the north-verging asymmetric anticline of the Oak Ridge-Montalvo trend, separated by a steeply south-dipping Oak Ridge fault which separates the fold from the Ventura basin on the north. The interpretation is that the Oak Ridge fault is a late Miocene and Pliocene age normal fault that has been cut, rotated, translated and/or reactivated by Quaternary compressive deformation and fault-propagation folding of the anticline. Figure 33 is a kinematic model that showing the structural evolution of the Oak Ridge fault and South Mountain anticline.

The central Ventura basin petroleum system is in many ways similar to that of the southern San Joaquin basin: 1) The Monterey Formation is the main source rock (Fig. 9A) and at South Mountain oil field the Monterey Formation is immature (Fig. 34A) as it is at the Wheeler Ridge oil field. 2) South Mountain oil field is bounded on the north by a deep central basin (fig. 30A) analogous to the Tejon depocenter. 3) The deep central Ventura basin is generating oil today at great depths (6-7 km; Figs. 34B, 35A) in a rapidly subsiding depocenter similar to the Tejon depocenter. 4) At the South Mountain oil field oil is migrating into a Quaternary age anticline similar to the Wheeler Ridge anticline. Oil generation in the Monterey Formation began only about 2 Ma in the deep central Ventura basin, and maturity modeling and biomarker data (Fig 18B) both suggest that the Monterey Formation is not mature enough to generate gas. This accords with the lack of free gas at South Mountain and the other oil fields in the central Ventura basin.

Figure 35B shows the sizes of oil fields in the Ventura basin. Most of the oil is in the west, with modest oil amounts in the east, and relatively small amounts of oil in the central area. A number of factors probably control this size distribution. The burial histories suggest that Monterey Formation maturity is one of the significant controls. Maturity at the base of the Monterey Formation appears to be less in the central Ventura basin than in the western or eastern portions of the basin (Figs. 34A, 9B). Another factor is the predominant south dip of the central Ventura basin (Figs. 32A-C). Analogous to the Wheeler Ridge area, most of the oil is migrating north away from South Mountain field and Oak Ridge trend, which are the most prominent traps in the central Ventura basin. In contrast most of the oil generated in the western Ventura basin migrates towards the giant Ventura field (Fig. 30A).

An interesting sidelight: thermal modeling of the western Ventura basin suggest that the very high sedimentation rates (1.0-1.5 m/ka) have reduced oil generation. ARCO’s Genesis program predicts that the sedimentation rates are high enough to prevent heat flow being maintained at steady-state conditions. This reduces subsurface temperatures, in turn reducing the quantities of oil generated. Another effect of the high sedimentation rates is the high heating rate undergone by the Monterey Formation. As shown by Pepper and Corvi (1995), high heating rates decrease oil generation.

Figure 33A-D. Model showing progressive deformation of a normal fault and growth strata by a fault-propagation fold.
Figure 34A. South Mountain field burial history showing % Ro. Exxon #39 well and surface geology composite. Heat flow = 1.15 HFU calibrated with DeRito (1989) heat flow and Sespe AFT temperatures (Hathon, 1992).

Figure 34B. Central Ventura kitchen burial history showing HC transformation ratio (%). Heat flow = 1.1 HFU Sespe #6 well.
Figure 35A. Central Ventura kitchen lower Monterey HC generation rate versus time.

Figure 35B. Ventura basin oil EUR distribution in MMBO.
Summary of South Mountain Oil Field
Gregory J. Cavette
Nuevo Energy Company
Santa Maria, CA

The South Mountain oil field was discovered in 1915 by the Oak Ridge Oil Company “South Mountain” #1 well, drilled to a depth of about 900 m with cable tools. Initial production was about 25 BOPD of 25° oil with no water cut from selected intervals between 455 to 900 m. The Main Area is an anticlinal trap along the upthrown side of the Oak Ridge reverse fault (Figs. 36A,B). Secondary trapping results from extensive normal faulting on the south limb of the anticline. Producing zones are fluvial sandstone of the lower part of the Sespe Formation. The “red bed” sandstone is poorly sorted and angular, and vary from thin silty meandering stream to thick conglomeratic braided stream deposits. Productive sands are in the 14 to 23 percent porosity range, with air permeability’s between 10 and 300+ millidarcies. Over 2200 acres have been proven productive with an oil column ranging from 180 to 2100 m. Production is mainly by solution gas drive in the Main Area and cumulative production to date is 106 MMBO (18° to 22° API) and 215 BCFG.

The Bridge Pool area of the South Mountain filed was discovered in 1955 by the Texaco-Union Richardson Earl #1 well flowing 205 BOPD of 33.6° oil, 6% cut, with 248 MCFD of gas. The total depth of the well was 2354 m in steeply-dipping sandstone beds of the Pliocene age middle Pico Formation beneath the Oak Ridge reverse fault. Lateral bowing of the footwall structure and up dip pinchout or fault truncation of the sandstone units combine to make the trap. The deep-marine turbidite beds have 22 to 26 percent porosity and 20 to 500 millidarcies permeability in the productive intervals. By the end of the 1960’s the pool had been delineated and fully developed by 91 wells (and many redrills). Both solution gas drive and water drive are present in the individual sandstone reservoirs of the Bridge Pool and cumulative production to date from the Bridge Pool is 44 MMBO (30° to 36° API) and 88 BCFG.

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Structural transect of the western Transverse Ranges, California: Implications for lithospheric kinematics and seismic risk evaluation

Jay Namson* ARCO Oil and Gas Company, 2300 Plano Parkway, Plano, Texas 75075
Thom Davis* 3937 Roderick Road, Los Angeles, California 90065

ABSTRACT
A retrodeformable cross section that integrates surface and subsurface data across the western Transverse Ranges, California, illustrates an actively developing fold and thrust belt that began forming at 2–3 Ma. High-level thrusts are interpreted to root in a mid-crustal detachment at 12–15 km depth, which coincides with the maximum depth of earthquakes. The cross section documents 53 km of convergence above the mid-crustal detachment; dividing this by the time since onset of deformation yields convergence rates of 17.6–26.5 mm/yr. The high-density lithospheric anomaly beneath the Transverse Ranges is related to subduction of lower crust and lithosphere below the mid-crustal detachment to balance the shallow crustal shortening. Thrust ramps coincide with zones of high seismicity in the Transverse Ranges; this suggests that ramp regions have the highest potential for compressive earthquake events: e.g., the recent Whittier Narrows earthquake of October 1, 1987 (M_s = 5.9), occurred along the eastern part of a ramp zone.

INTRODUCTION
The Transverse Ranges of southern California consist of a series of young, east-west-trending ranges and valleys that cut across the northwest-trending topography of California. The ranges are underlain by a thick sequence of late Mesozoic and Cenozoic age strata that rest unconformably on a variety of basement types. The Transverse Ranges are undergoing active north-south shortening as documented by late Pliocene and Quaternary folds, thrust faults, and reverse faults (Reed and Hollister, 1936; Jahns, 1954; Dibblee, 1982a), geologically measured north-south convergence (Savage et al., 1986; Christodoulidis et al., 1985), and numerous compressive fold and thrust systems with north–south–directed P-axes (Hadley and Kanamori, 1977; Yerkes and Lee, 1979; Webb and Kanamori, 1985).

Geophysical studies of the Transverse Ranges reveal several features of the lithospheric structure: (1) The majority of earthquakes occur above 12–15 km (Hadley and Kanamori, 1977). (2) Seismic studies indicate an east-west-trending, slab-shaped, high-velocity anomaly within the upper mantle (Hadley and Kanamori, 1977; Raïkes, 1980; Humphreys et al., 1984). (3) Gravity studies indicate an east-west–trending, high-density gravity anomaly under the central Transverse Ranges (Sheffels and McNutt, 1986). Several geophysical and geological models have been proposed to explain the above observations. The 12–15 km seismicity floor and the low-angle, compressive earthquake mechanisms have been interpreted to coincide with a mid-crustal, subhorizontal detachment (Hadley and Kanamori, 1977; Webb and Kanamori, 1985). On the basis of regional geologic relations and some of the previously mentioned geophysical observations, Yerkes (1981, 1983) suggested that the reverse faults of the Transverse Ranges rooted into a mid-crustal detachment. Yerkes (1981) further proposed that this detachment separated an upper brittle tectonic "blank" from a lower plate undergoing plastic deformation. Bird and Rosenstock (1984) developed a kinematic model of the Transverse Ranges using late Cenozoic slip rates that showed significant convergence in the western Transverse Ranges and predicted mantle-lithosphere downwelling, which is consistent with the observed upper-mantle seismic velocity and gravity anomalies.

In this paper we present a geologic model of the upper crust beneath the western Transverse Ranges (Fig. 1) based on a balanced regional cross section (Fig. 2a) that 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-bend or fault-propagation folds (Suppe, 1985) developed above thrust faults stepping upsection from a regional detachment that coincides with the floor of seismicity. The regional cross section has been restored to late Pliocene time using the line-length method (Fig. 2b; Woodward et al., 1985). The retrodeformability of the cross section tests the internal consistency of the structural interpretation and shows that the section is balanced. The cross section and restoration are used to (1) estimate the amount of crustal convergence, (2) provide an independent estimate of the depth of the lithospheric anomaly, and (3) estimate the convergence rate across the western Transverse Ranges since late Pliocene time. Because the Transverse Ranges are seismically active, the cross section can be used to understand the relation between geologic structures and zones of seismicity.

The cross section is a two-dimensional solution that assumes minimal motion out of the plane of the cross section, with the exception of the San Andreas fault, during the past 3 m.y. We believe this assumption is compatible with the western Transverse Ranges geology, as we demonstrate in the following discussion.

CROSS-SECTION DESCRIPTION
The regional cross section was originally constructed at a scale of 1:24000 by using surface maps (Dibblee, 1982b, 1982c; California Division of Mines, 1973; Dibblee and Nilsen, 1973; Davis, 1983; Davis and Duebendorfer, 1987) integrated with well data from numerous oil fields and wildcats wells along the transect. These data constrain the fault and fault geometries that are used to construct the balanced interpretation. The Cenozoic structural history of the western Transverse Ranges is complex; here we focus only on the latest phase of north-south convergent deformation that developed during the past 2–3 m.y.

Starting at the south, the section begins in the West Montalvo oil field, which is part of an east-west anticlinal trend more than 60 km long. Anticlines along the trend are generally asymmetric, having steep north limbs and gentle south limbs. On the basis of the asymmetric shape of the anticline, the fold is interpreted to be a fault-propagation fold above the postulated South Mountain thrust. The Oak Ridge fault lies along the southern boundary of the Ventura basin and separates thick upper Miocene to Pleistocene strata of the basin on the north from a coeval but much thinner section to the south of the fault. At shallow levels the fault is north dipping, and it generally occurs on the north limb of the asymmetric anticlines. The Oak Ridge fault is interpreted to be a late Miocene to...
Piocene north-dipping, normal fault (Namson, 1987) accommodating subsidence and sediment accumulation (Yeats, 1977). The present south dip of the upper part of the fault is the result of rotation by Quaternary anticlinal folding (Fig. 2a) and along strike to the west, the rotated part of the normal fault has been reactivated as a reverse fault (Namson, 1987).

The next major structure to the north is the Ventura Avenue anticline. The anticline has been interpreted to be rootless (Nagle and Parker, 1971), and Yeats (1983) interpreted the fold as detached above a ductile sequence of Miocene rocks. Namson (1987) interpreted the fold as a series of wedge-shaped imbricate thrusts that are rooted at the base of the Miocene (Fig. 2a), 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 spay of the San Cayetano fault (SC1) which steps up from a lower detachment within the Cretaceous strata to an upper detachment at the base of the Miocene sequence. (The San Cayetano thrust comes to the surface about 10 km east of the cross section; see Fig. 1.) At the surface, the south limb of the Lion Mountain anticline is composed of a thick sequence of Oligocene through Miocene strata, and the bedding-plane Lion Mountain fault occurs at the base of the Miocene sequence (Dibblee, 1982b). Slip on the upper detachment of the fault-bend fold (base of Miocene) is partitioned between the wedge-shaped imbricates responsible for the Ventura Avenue anticline and the Lion Mountain fault, which is a back thrust off the upper detachment.

North of the Lion Mountain anticline the Santa Ynez-Topatopa mountains are an east-west-trending anticlinal uplift more than 150 km long. Where the cross section intersects the range, the south limb of the antiform is overturned. Uplift and folding of the range occurred during the late Miocene and Quaternary (Dibblee, 1982b; Yeats, 1983). The Santa Ynez fault occurs along the north flank of the Santa Ynez-Topatopa mountains and separates them from the San Rafael Mountains to the north. The Santa Ynez fault has been interpreted in various ways. McCullough (1981) hypothesized left-slip movement of 37 km, which occurred mostly during Miocene time. In contrast, Hall (1981) believed the fault had considerable right slip during Miocene time. Gordon (1978) and Dibblee (1982b) suggested that the Santa Ynez is primarily a dip-slip fault and discounted the large amounts of strike slip because the fault terminates at both the eastern and western ends of the Santa Ynez-Topatopa mountains. We interpret the Santa Ynez fault as a north-vergent back thrust associated with a south-vergent Oligocene thrust system that uplifted the ancestral San Rafael Mountains (Reed and Hollister, 1936). This explains the origin of the regional angular unconformity between upper Oligocene through Miocene strata and upper Mesozoic through lower Tertiary strata, and gives a structural explanation for the Ynezian orogeny (Dibblee, 1982b; see Namson, 1987, for more detail). The configuration of the Oligocene thrust system is shown in the restoration (Fig. 2b).

The Quaternary antiformal structure of the Santa Ynez-Topatopa mountains is interpreted to be related to two stacked anticlines having cores of Cretaceous strata. The deeper anticline is a fault-bend fold associated with the lower spay of the San Cayetano fault (SC1), and the upper anticline is a fault-propagation fold associated with an upper spay of the San Cayetano thrust (ST2, Fig. 2a). The spays merge downward into a common detachment of the main San Cayetano thrust. The Santa Ynez fault is folded and cut by Quaternary structures. Minor Quaternary reactivation of the Santa Ynez fault is interpreted as shearing associated with folding.

Between the Santa Ynez fault and the Pine Mountain thrust are several tight, small folds that terminate against the Pine Mountain thrust. Near its surface trace, the Pine Mountain thrust overrides the north limb of a syncline that contains strata as young as Pliocene. The syncline is interpreted to be the front of a fault-propagation fold on a spay 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 (Dibblee, 1982c). This regional unconformity is only moderately folded and does not dip as steeply as the underlying Eocene strata; it is probably associated with the Ynezian orogeny.

Figure 1. a: Generalized seismotectonic map for western and central Transverse Ranges (after Yerkes, 1985) showing cross-section line in Figure 2. Stipple indicates zones of high seismicity characterized by compressive (north-south) focal mechanisms, east-west-trending Quaternary folds, thrust and reverse faults, and steep range fronts. BPF = Big Pine fault; GF = Garlock fault; LA = Los Angeles; SAF = San Andreas fault; SB = Santa Barbara. b: Generalized seismotectonic map of part of western Transverse Ranges showing cross-section line of Figure 2. Labels as in part a, plus AM = Alamo Mountain; BK = Bakersfield; FM = Frazier Mountain; MP = Mount Pinos; ORF = Oak Ridge fault; OZF = Ozona fault; PTS = Pleito thrust system; PM = Pine Mountain; PMT = Pine Mountain thrust; RFM = Red Mountain fault; SBC = Santa Barbara Channel; SCT = San Cayetano thrust; SEM = San Emigdio Mountains; SGE = San Gorgonio thrust; SM = Sierra Madre; SRM = San Rafael Mountains; SSJB = southern San Joaquin basin; SYF = Santa Ynez fault; SYM = Santa Ynez Mountains; TTM = Topatopa Mountains; VA = Ventura Avenue anticline; VEN = Ventura; WRA = Wheeler Ridge anticline; WWF = White Wolf fault. Contour lines about SEM, MP, and SAF are lines of equal Bouger anomaly (5 mgal).
Figure 2. a: Structural transect across western Transverse Ranges. 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 = Plaito 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 motion of San Andreas fault. b: Line-length restoration of late Pliocene through Quaternary compressive structures of transect in part a. Comparison of transect length between deformed section (123 km) and restored section (176 km) yields 53 km of convergence since late Pliocene time (~3.0 Ma). This gives shortening of 30% and convergence rate of 17.6 mm/yr. Section indicates restored positions of Oligocene compressive structures, late Miocene-Pliocene normal faults, and San Andreas strike-slip offset. San Andreas fault restores to vertical fault, separating terrain now offset horizontally about 100 km. Labels as in a.
The cross section intersects the San Andreas fault between the Big Pine and Garlock faults; surface maps by Davis and Duebendorfer (1987) indicate that this part of the San Andreas fault is a narrow zone with no evidence of significant dip-slip offset. Well-constrained horizontally offset drainage lines in the nearby Carrizo Plain indicate right-lateral slip rates of 33.9 + 2.9 mm/yr for the past 3.7 ka and 35.8 + 5.4/-4.1 mm/yr for the past 13.25 ka (Sieh and Jahn, 1984).

Adjacent to and directly north of the San Andreas fault is the north-dipping Caballo Canyon fault, which contains crystalline basement in the hanging wall and Oligocene strata in the footwall. Davis (1986) interpreted the Caballo Canyon fault to be a south-vergent thrust that lifted the ancestral San Emidigio Mountains during Oligocene time (Ynezian orogeny?). Along the north flank of the San Emidigio Mountains is the late Pliocene to Quaternary Pleito fault system, which consists of several south-dipping (20°-30°) thrust faults constrained by well data as deep as 3 km (Davis, 1983, 1986). Well data in this area show that major anticlines are formed by fault-bend or fault-propagation folding, and slip on some of the large thrusts does not reach the surface (Namsion and Davis, 1988). 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 (Davis, 1986; Medwedeff, 1987). 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 Plio-Pleistocene strata of the San Emidigio Mountains from coeval but much thicker strata of the southern San Joaquin basin. Well data from the downright 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 late Miocene to Pliocene normal fault whose upper part has been subsequently folded. The asymmetric North Tejon anticline suggests that it is a fault-propagation fold above a north-vergent basement thrust. This thrust has the appropriate location, orientation, and sense of slip to be the cause of the 1952 Arvin-Tehachapi earthquake (Mw = 7.6; Davis and Lagoe, 1987).

Movement on this thrust would also fit the area of coseismic topographic uplift (Stein and Thatcher, 1981).

The cross section shows the splays of the Pleito thrust system to 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 (at 6.5 km) 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. The south dip and shallow detachment of the San Andreas fault are consistent with two observations. (1) Regional gravity study of the western big bend area reveals a large positive gravity anomaly with a crest located north of the San Andreas fault (SEM, Fig. 1b; Griscom and Oliver, 1980). The position of the crest corresponds to outcrops of dense basement rocks of ophiolite, tonalite, and mafic gneiss. The south flank of the anomaly does not terminate at the surface trace of the San Andreas fault but extends 5-6 km south of the San Andreas fault; this suggests that high-density rocks extend southward beneath the surface trace of the San Andreas fault for some distance. (2) The location of the topographically highest part of the western Transverse Ranges, the Mount Pinos and Frazier Mountain area, is located immediately above the large crustal ramp along which the San Andreas is shown to be detached.

**IMPLICATIONS**

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 can be no younger than 2.0 Ma (Ventura basin; Yeats, 1983), and regional stratigraphic evidence suggests that it is no older than 3.0 Ma (Crowell, 1966; Rockwell, 1982; Davis, 1983). By using this range of time values, the convergence rates north and south of the San Andreas fault are determined to be 6.3-9.5 mm/yr and 11.3-17.0 mm/yr, respectively. The total convergence rate across the onshore part of the western Transverse Ranges is 17.6-25.5 mm/yr.

The convergence rate is useful for estimates of recurrence times of moderate to large earthquakes along north-south segments of the Transverse Ranges. If we assume no aseismic creep and that a thrust moves 1-2 m at depth during a moderate-size earthquake, then it would require an event every 57-113 yr along a north-south section to accommodate the estimated convergence rate (17.6 mm/yr) for 3.0 Ma. This recurrence interval is about an order of magnitude greater than that derived by Yeats and Berryman (1987). The general application of using balanced cross sections to estimate recurrence times can be applied to specific structures (Namson and Davis, 1986) and should be combined with other methods to better forecast both the time and location of future earthquakes.

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 m.y. (Fig. 3). 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).

The cross section presents a useful structural framework for explaining the distribution, focal depths, and compressive focal mechanisms of earthquakes in the western and central Transverse Ranges. Yerkes (1985) showed the distribution of 42 known damaging earthquakes from 1800 to 1978 (MM > VII) in the Transverse Ranges; some of these are shown in Figure 1a. The distribution of these events defines three east-west-trending zones that coincide with structural trends: Santa Monica, Santa Ynez, San Gabriel, and San Emidigio. Known focal mechanisms for events within these zones are overwhelmingly compressive (Yerkes, 1985; Fig. 1a). The Whittier Narrows earthquake (Mw = 5.9) of October 1, 1987, occurred along the Santa Monica zone. The cross section traverses the latter two trends and indicates that the seismicity is concentrated along the major thrust ramps of the western Transverse Range transect. Many of these thrust ramps never reach the surface or reach the surface through complicated trajectories. It is therefore difficult, if not impossible, to evaluate their seismic potential from surface studies alone. Balanced cross sections that integrate surface and subsurface data are one technique that can determine the geometry and slip rates of thrusts for seismic risk evaluations.

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.
Figure 3. Schematic cross section showing how shortening below mid-crustal detachment of Transverse Ranges is accommodated by subduction of lower crust and lithosphere of Pacific plate. Regional transect suggests that 53 km of subduction is necessary to balance shortening above detachment. Slab is 60 km thick, as suggested from seismic tomography (Humphreys et al., 1984), and extends to depth of about 120 km, which is consistent with observed high-velocity anomaly in western Transverse Ranges (Humphreys et al., 1984). A and T indicate motion of San Andreas fault.

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Nanson and Davis (1988) presented a balanced cross section across the western Transverse Ranges and the Big Bend of the San Andreas fault and made a number of inferences about the style and rate of shortening. A good estimate of the deformation across this area would provide needed constraint on regional tectonics and seismic hazard, and as such their work could be very useful. We have problems with three major aspects of their model and feel that these problems, if unresolved, are substantial enough to invalidate many of their conclusions.

The first issue is the "subduction" of the lower crust. The proposed 53 km of shortening is "balanced" by an equivalent amount of convergence and downward motion of the lower crust and mantle lithosphere. Nanson and Davis did not discuss the details of this process; however, they cited the work of Bird and Rosenstock (1984), Humphreys et al. (1984), and Sheffels and McNutt (1986) as supportive of their model of balancing upper crustal shortening with lower crustal subduction. Bird and Rosenstock (1984, p. 946, 955, 956) were careful to state that only the upper mantle is going down under the Transverse Ranges. They detached the mantle from the crust at the Moho, not at the ~15 km "brittle-ductile" transition proposed by Nanson and Davis, for the obvious reason that they had no evidence for crustal subduction. Bird and Rosenstock (1984) stated that the solution to resolving the issue is mapping out the depth to the Moho boundary, which was done by Hearn (1984). Hearn found that there are only a few kilometres of Moho depression under the Transverse Ranges relative to "typical" continental southern California.

Humphreys et al. (1984) imaged the upper mantle, proposed small-scale convection to explain the velocity anomaly under the Transverse Ranges, and called upon upper mantle flow to support the relief. Sheffels and McNutt (1986) proposed flexural support for the Transverse Ranges, caused by "continental subduction." Whereas Sheffels and McNutt's (1986) paper leads one to infer major crustal subduction, the values they are proposing are trivial; they stated (p. 6428) that the thickening of the crust under the western Transverse Ranges is less than 2 km. Nanson and Davis also failed to cite a correction (Sheffels and McNutt, 1987) that brings Sheffels and McNutt's work into agreement with Humphreys et al. (1984) on the density of the velocity anomaly under the Transverse Ranges, further diminishing the need for forces other than those derived from small-scale convection and crustal strength to support the Transverse Ranges.

In summary, Hearn (1984), Humphreys et al. (1984), Bird and Rosenstock (1984), and Sheffels and McNutt (1986, 1987) all agreed that there has been minimal crustal subduction under the Transverse Ranges, especially in the western Transverse Ranges. Although the various models contain disagreements, none of the observations support the magnitude of crustal subduction proposed by Nanson and Davis. One obvious resolution to the problem of how tremendous upper crustal convergence can be accommodated without significant lower crustal subduction is that far less convergence has occurred than proposed. Another is that the convergence occurred over a much longer time, so that surficial erosion and spreading of the lower crust thinned the crust as it was shortened. Although these may be partial solutions, we are compelled by the evidence that major, recent, shallow shortening has occurred in the western Transverse Ranges. Because the crust is only slightly thicker than the surrounding continental crust, one could speculate that it was once anomalously thin. If the 53 km of shortening proposed by Nanson and Davis is taken out and no crust is lost from the system, the initial thickness of the crust would have been <20 km, essentially the crustal thickness under the continental borderland (e.g., Hearn, 1984). The western Transverse Ranges would therefore have been a part of the borderland and thickened into "typical" continental values by the deformation proposed by Nanson and Davis. We do not believe that the geology supports this solution; however, it may be worth considering. Our preferred resolution of major surficial shortening without substantial crustal thickening lies in the kinematic relation between the convergence and regional strike-slip faulting. We have proposed (Weldon and Humphreys, 1986) that the convergence in the western Transverse Ranges is related largely to a left step in a zone of right-lateral strike-slip deformation between faults north and south of this region, and that the convergence in the southern San Joaquin basin is related to the Big Bend in the San Andreas and the western terminations of the Garlock fault. Perhaps the lower crust has less unfavorable geometries than the upper crust and can move more smoothly through these regions. The upper crustal convergence proposed by Nanson and Davis may be "balanced" by lateral movement in and out of the plane of the section by strike-slip motion and block rotations.

The second major problem with Nanson and Davis's model is strike-slip motion through the cross section. Lateral motion allows one to move material in or out of the plane of the section, which invalidates the "balancing" done simply in the plane of the section. Nanson and Davis claimed that the only place one need worry about is the San Andreas (discussed more below); we disagree. There has been substantial rotation and lateral shear across the southern half of their section (e.g., Hornafius, 1985; Dibblee, 1982). It is possible that much of the rotation and lateral shear preceded the time period discussed here; however, considerable nonconvergent deformation occurred since the deposition of the Eocene section, so if it does not affect the current kinematics it would have to affect the initial geometry (shown as quite simple in Fig. 2b of Nanson and Davis, 1988). In fact, lateral slip and block rotation have not been included at all.

Two special problems arise from the fact that the balancing occurs across the San Andreas fault. First, the two pieces of their cross section, which are across the San Andreas from each other today, were separated by about 100 km when deformation began. Balancing these spatially and kinematically unrelated regions lacks justification until they are across the San Andreas fault from each other. However, it is clear that the low-angle feature that offsets the San Andreas is critical to Nanson and Davis's entire model. The presence of their proposed offset of the San Andreas fault by a low-angle structure also causes problems when one considers the well-documented right-lateral sense of the San Andreas fault. North and south of the proposed lateral ramp in the San Andreas the fault is vertical (evidence includes a vertical belt of seismicity down to ~15 km in places where seismicity exists). Because the vertical parts of the San Andreas fault are connected to the proposed low-angle ramp, lateral motion on the fault will produce uplift as the western block rides up the lateral ramp and extension where the San Andreas becomes vertical again and the western block rides down the ramp. This is analogous to a snowplow lifting the snow as its curved blade is pushed forward through the snow and dropping it as the plow passes. In this case the "plow" is the crust on the east side of the proposed lateral ramp in the lower San Andreas fault. The magnitude of this hypothetical deformation would be comparable to the volume displaced by the ramp, which suggests that as the western block moves up
the ramp, a dip panel about 20 km wide and more than 8 km high (at the crest by the fault) would form. It would approach 100 km long, the displacement across the San Andreas during the time considered here. One could argue that the proposed ramp grew with time and that the dip panel would be lowered as the backside of the bulge in the San Andreas fault passed by, but it is clear that nothing like this has occurred. Offsetting the San Andreas fault with a low-angle structure solves the contractile balance in the plane of the cross section, but creates unsolvable problems when the much greater lateral motion is considered.

The third problem is whether the western Transverse Ranges ever looked like the initial section proposed in Figure 2b of Nanson and Davis (1988, p. 677). A major justification for balancing a section is that if you could go back in time and examine the region prior to deformation, it would look like the retrodeformed section. The cross section shown in Figure 2b looks like one through the Rocky Mountains, not across an active transform margin. Because there are virtually no data constraining the central part of the section (note how few wells actually penetrate the pre-Oligocene strata, and how much of the deformation is accommodated there), the thickness and original geometry of the Eocene and older rocks at the starting time of 2–3 Ma is unknown. In effect, the units are assumed to have virtually constant thickness, broken only by the relatively few and simple normal and reverse faults shown in Figure 2b. Because there are no data with which to test this hypothesis, it is conjecture. In the absence of data one might suggest that this configuration is the simplest and therefore the most defensible; however, the degree to which this assumption is approached greatly affects the total shortening and the inferred slip rate, something the casual reader is not likely to appreciate. The well-documented rotations, lateral slip, and proximity of the region to the plate and continental boundary almost certainly require that the region was much more complexly deformed by 3 Ma; therefore, retrodeforming to an initially craton-like distribution of thicknesses is unjustified.

Construction of balanced cross sections across a transform boundary necessarily focuses on the convergence or extension associated with the local geometry of the boundary. We suggest that the dip-slip faulting must be understood in the context of the geometry of the more fundamental strike-slip faults in the transform boundary and the kinematics of the overall crustal deformation.

REPLY

Jay Nanson, Thom Davis, Davis & Nanson Consulting Geologists, 1545 N. Verdugo Rd., Suite 9, Glendale, California 92108

1. Weldon and Humphreys take issue with our model of subducting the lower crust and upper mantle because subduction of the lower crust is not supported by geophysical studies. Weldon and Humphreys suggest crustal thickening as an alternative, but they question whether the geology supports this solution. They favor “balancing” shallow crustal convergence in the lower crust by lateral movement or rotation on strike-slip faults out of the plane of the section. Subduction of lower crust is required in many areas of convergence (Laubscher, 1988). The ability of geophysical techniques to detect lower crustal subduction may be hampered by phase changes that cause the lower crust to be absorbed into the upper mantle (Laubscher, 1988). Our lithospheric subduction model is only one possible solution to balancing shallow crustal shortening; we have also suggested lithospheric thickening (Nanson and Davis, 1988). Lower crustal thickening also quantitatively fits our model. The lower crust thickens from 30 to 34 km from the borderland across the southern margin of the western Transverse Ranges (Keller and Prothero, 1987; Hearn, 1984). The lengths of our cross section and restoration are 123 km and 176 km, respectively. Our proposed 53 km of shortening would take an unshortened 23-km-thick crust to a shortened crustal thickness of 33 km, which is in close agreement with the geophysical measurements in the borderland and western Transverse Ranges, respectively. Weldon and Humphreys’s doubt that the geology of the modern-day borderland resembles the preconvergence geology of the western Transverse Ranges is unfounded. Nearly 50 years of study of marine geology, paleoenvironments, and stratigraphy have drawn comparisons between the Neogene geologic histories and settings of the two areas (e.g., Shepard and Emery, 1941; Teng and Gorsline, 1989).

The solution favored by Weldon and Humphreys cannot work. It is not possible to balance shallow crustal convergence in the lower crust by lateral motion because lateral motion does not yield shortening. Volume conservation requires that shallow crustal shortening be balanced in the lower crust and upper mantle by tectonic thickening or subduction. Balanced cross sections such as ours tell how much thickening or subduction must occur.

2. Weldon and Humphreys disagree with our balanced cross section approach because they say there have been strike-slip motions on faults that are not accounted for in our cross section. This issue was discussed in Nanson and Davis (1988). Weldon and Humphreys present no evidence of significant late Pliocene and Quaternary lateral motion on faults in our cross section, nor do the references they cite. Evidence for coeval rotations is weak; if they have occurred, they are minor.

3. Weldon and Humphreys suggest two problems with balancing cross sections across the San Andreas fault: (1) it is unjustified because the regions across the San Andreas are kinematically and spatially unrelated, and (2) offset of the San Andreas fault by a ramp is incompatible with the geology. Balancing the blocks north and south of the San Andreas fault separately is justified because we assume the San Andreas fault was originally vertical and therefore use it as a reference line in restoration; it is irrelevant how much strike slip has taken place. Weldon and Humphreys assume that the ramp cutting the San Andreas fault must go from vertical to low angle and back to vertical. They state that strike-slip motion along such a ramp geometry would produce large amounts of uplift and a particular deformational geometry that is not observed. Weldon and Humphreys’s suggestion is only one of several kinematic and geometric possibilities for ramp/San Andreas fault interaction. For example, one model that requires neither uplift nor the deformational geometry proposed by Weldon and Humphreys is material moving in the strike direction of the ramp accompanied by near-horizontal simple shear. This model, which is only one of several possibilities, is consistent with both the geology and our cross-section interpretation. Constraining the three-dimensional geometry requires additional balanced cross sections and geophysics.

4. Weldon and Humphreys question our restoration because (1) it looks like the Rocky Mountains, (2) it does not fit their vision of an active transform margin, and (3) there are no data to constrain the original thickness and geometry of Eocene units. Our restoration does not look like the Rocky Mountains, and we refer Weldon and Humphreys to the classic works of Bally et al. (1966), Price and Mountjoy (1970), and Royse et al. (1975). One purpose of our analyses is to provide a quantitative model of the southern California margin just prior to late Pliocene and Quaternary convergence, not to accommodate a preconceived notion of transform margin geometry. Our cross section integrates an amount of data substantially greater than any preexisting structural interpretation across the western Transverse Ranges and explains the geology at a 1:24000 map scale. The thickness and geometry of the Eocene and other units are extremely well constrained by detailed maps, measured sections, and biostratigraphy (references cited in Nanson and Davis, 1988). We have projected the surface data to depth by techniques commonly used by structural geologists in mountain belts since the early part of this century. The restored geometries of Eocene-age and other units are determined by unfolding angular unconformities and successively restoring beds to the horizontal, following Steno’s law of original horizontality of sedimentary beds.

Our approach to understanding the overall crustal deformation is to develop quantitative, restorable, and integrated models that resolve the map-scale geology. One result is the amount of crustal shortening recorded
in folding, which has been ignored or only partially considered in previous tectonic models. With the exception of the San Andreas fault, the fundamental late Pliocene and Quaternary structures of the western Transverse Ranges are folds and thrust faults, not strike-slip faults.

**COMBINED REFERENCES CITED**


**COMMENT**

Robert S. Yeats, Gary J. Huffine, Department of Geology, Oregon State University, Corvallis, Oregon 97331-5506

Naman and Davis (1988) used the difference between present-day and restored length of their cross section as evidence for contraction of 53 km, contraction rates of 17.6–26.5 mm/yr, and recurrence intervals of 50–100 yr for earthquakes on some part of their section. Their technique leads to useful insights about subsurface structure. However, balancing the cross section does not make it unique, and different cross sections using the same observations produce different values for total contraction. Because Naman and Davis (1988) did not consider the uncertainties in their model, their calculations of contraction rates and recurrence intervals are of little value in estimating seismic risk. Furthermore, we disagree with the interpretation of the southern 40 km of their cross section, which is mainly drawn from Yeats (1979). We focus our comments on this part of the section, where most of the contraction has occurred.

For a cross section to be balanced, it must be drawn in the direction of tectonic transport so that the displacement of elements in the section may be measured directly in the plane of the section as tectonic shortening between undeformed and deformed states. Naman and Davis’s cross section is north-south, whereas tectonic transport is north-northeast to northeast, on the basis of earthquake focal mechanisms and borehole breakouts (Zoback et al., 1987; Yeats et al., 1988). The direction of maximum principal compressive stress (σ_{1}) is nearly normal to the San Andreas fault, not normal to the trend of the Transverse Ranges (Zoback et al., 1987). Accordingly, the estimates of shortening by Naman and Davis (1988) are at least 10% too low, on this basis alone.

Naman and Davis (1988) interpreted the Oak Ridge fault as a late Miocene to Pliocene north-dipping normal fault rotated by Quaternary anticalinal folding and reactivated as a reverse fault. This interpretation ignores the possibility that these strata underwent flexural-slip folding, as documented for folded strata of the same age and facies on the north side of the Ventura basin (Yeats et al., 1981). Direct evidence of shortening in the Pliocene is provided in cross section E–F in Figure 7 of Yeats et al. (1981), in which the Oak Ridge fault tip does not extend upward into the Pliocene. In this cross section, the length of a 3 Ma horizon is about 1.5 km greater than that of a 1 Ma horizon, indicating that shortening occurred in the time between deposition of the two horizons, rather than extension, as claimed by Naman and Davis (1988). Shortening is also documented between these same horizons in an adjacent area (cross sections C-D of Fig. 7), where the fault tip extends upward to the 1 Ma horizon, and the cut-off angles between bedding and fault are similar to those shown by Naman and Davis (1988).

Naman and Davis (1988) showed the Ventura Avenue anticline as a rootless structure above a decollement in the early Miocene, following Yeats (1983). But their decollement goes the wrong way; the fold is interpreted as related to a south-vergent blind thrust related to the San Cayetano fault (their SCT1). The Ventura Avenue anticline and the San Miguelito and Rincon anticlines farther west are fault-propagation folds updip from north-verging, south-dipping reverse faults (Barnard, Padre Juan, and C-3 faults, respectively). Yeats et al. (1988) showed that these folds are related to a buried frontal thrust of the Oak Ridge fault to the south, not a blind thrust to the north.

The Naman and Davis (1988) estimate of total shortening depends on their highly speculative interpretation of the Santa Ynez and San Cayetano faults at depth. We regard their positioning of ramps and flats within the Mesozoic at 10–15 km depth beneath the mountains north of the Ventura basin as arbitrary, unsupported by geophysical or geological evidence. Their two ramps have a height of 9 km, leading to a shortening of 14 km. By varying the height of these ramps from 7 to 12 km, the shortening figure varies from 19 to 12 km. Furthermore, their depiction of the San Cayetano fault as a low-angle thrust at depth does not consider constraints on the position of the fault at depth, based on earthquakes located by Yerkes and Lee (1979) and Simila et al. (1987; G. Simila, personal commun.).

The complicated interpretation of structure beneath the mountains north of the Ventura basin includes major Oligocene thrust structures that remain unrestored on their balanced cross section. There was major tectonism in the Transverse Ranges during the Oligocene; however, this was not contractile, but extensional tectonism during deposition of nonmarine sedimentsary and volcanic rocks (Simmler and Vasquez Formations) into grabens and fault-angle depressions (Muchberger, 1958; Bohannon, 1975).

Naman and Davis (1988) based their convergence rates on the initiation of convergence at 2–3 Ma, assuming equal rates of convergence from then until now. However, the north dip of Miocene and older strata south of West Montalvo predates the deposition of the Siskiyou Formation, which onlaps this north-dipping homocl ine; this means that their “South
Mountain thrust," which presumably controls this homocline, is 4–5 Ma. In contrast, the Ventura Avenue anticline began to form after 0.4 Ma and perhaps after 0.2 Ma. Displacement on the Oak Ridge fault accelerated in the past 2 m.y. (Yeats, 1988), and the slip rate for the past few hundred thousand years locally is as much as an order of magnitude faster than the rate from 4 to 3 Ma. Because the slip rate for the past few hundred thousand years is the only rate important to slip-rate and recurrence-interval calculations, convergence rates based on a restored cross section at 3 Ma have little bearing on seismic risk evaluation.

On the other hand, we agree with Namson and Davis (1988) that balanced cross sections can be of value in calculation of convergence rates across the Transverse Ranges (Yeats et al., 1988), but our use is much more conservative than theirs. If a decollement horizon can be located independently, and the thickness of strata above the decollement is known, then the amount of convergence can be determined by area-balancing the section, even if the internal details of the cross section are not known. A section is area-balanced by dividing the cross-sectional area of the deformed sequence by the thickness of the undeformed sequence to give the original bed length of the undeformed sequence. If it is assumed that no rock moves in or out of the section during deformation, the difference between the original bed length and the present length of the deformed sequence is the amount of shortening (Dahlstrom, 1969; Woodward et al., 1985). This can be done for the decollement at the base of the Miocene shale section (Yeats et al., 1988) and, to a lesser extent, for the base of the seismogenic zone, established by flat-thrust earthquakes (Webb and Kanamori, 1985). In an area of extensive subsurface control, several cross sections can be drawn along strike by using independent data sets. The total convergence represents the approach of blocks north and south of the Transverse Ranges, and convergence should be the same for all sections or should vary smoothly. Convergence values that pass this consistency test are more likely to be correct.

Balanced cross sections through the upper crust can provide valuable insights, such as the depiction of the Lion Mountain anticline by Namson and Davis (1988) as a fault-bend fold above a blind frontal thrust related to the San Cayetano fault and the interpretation of the Lion fault as a passive backthrust related to the deeper blind thrust (cf. Hufnile, 1988). The cross section is admissible, as Dave Elliott put it, but it is not unique. Therefore, values for contraction are not useful for seismic risk evaluations unless they are constrained by admissible cross sections giving maximum and minimum values. In addition, the Namson and Davis (1988) cross section is less in accord with available data than other solutions.

REPLY

Jay Namson, Thom Davis, Davis & Namson Consulting Geologists, 1545 N. Verdugo Rd., Suite 9, Glendale, California 91208

Yeats and Hufnile raise several issues about the usefulness, originality, and accuracy of our recent structural interpretation. We address the issues as follows.

1. Yeats and Hufnile disagree with our interpretation of the 40-km-long segment of the Ventura area, yet state it is mainly drawn from Yeats’s earlier work. Our cross section is 115 km long; well-log correlations of only a 15-km-long segment are after Yeats (1979) and are cited in the original detailed work (Namson, 1987). Our structural interpretation bears little resemblance to that of Yeats other than location and showing late Cenozoic convergence.

2. Yeats and Hufnile state that our cross section is not in the direction of tectonic transport which they believe is defined by focal mechanisms and borehole elongations. Although this approach is novel, we believe Yeats and Hufnile have confused stress and strain. Borehole elongations provide some information on the instantaneous state of stress, and focal mechanisms provide some data on the instantaneous stress and instantaneous fault slip. These data do not provide the tectonic transport direction (strain) over the past 2–3 m.y. Structural cross sections (balanced or otherwise) should be drawn perpendicular to the strike of regional fold axes and thrusts (in compressional terranes), because these define the direction of tectonic transport and insure that the beds will appear in their true thickness and that geologic surfaces will show their true dip geometry (Suppe, 1985, p. 60; Woodward et al., 1985, p. 47; Ramsay and Huber, 1987, p. 365). Our section is drawn perpendicular to the average strike of the regional folds and thrusts.

3. Yeats and Hufnile disagree with our interpretation that the Oak Ridge fault is a late Miocene to Pliocene normal fault rotated by Quaternary compression, and state that we ignored flexural-slip folding. Our construction technique assumes that flexural-slip folding is the main deformation mechanism, but this is irrelevant with reference to the origin of the Oak Ridge fault. Yeats and Hufnile’s observation of increasing shortening between 1 and 3 Ma horizons is consistent with our interpretation of the crossover from normal faulting to compression between 2 and 3 Ma. Because Yeats and Hufnile do not address our principal evidence in support of a late Miocene to Pliocene Oak Ridge normal fault, we still consider this the most reasonable geological interpretation.

4. Yeats and Hufnile state that our interpretation of the Ventura Avenue anticline follows Yeats’s (1983) interpretation of a rootless detachment fold above a decollement. However, his most recent interpretation (Yeats et al., 1988) changes it to a fault-propagation fold. They further state that our decollement transport direction is going the wrong way because it is not in agreement with their recent interpretation. Nagle and Parker (1971, Fig. 14) first showed the Ventura Avenue anticline as a rootless fold. Our interpretation of the anticline is that it is an imbricate wedge of fault-bend folds above a decollement in the lower Miocene. The symmetric geometries of the Ventura Avenue, San Miguelito, and Rincon anticlines do not resemble the asymmetric fault-propagation fold geometry (see Suppe, 1985) as proposed by Yeats et al. (1988).

We have drawn a south-vergent thrust system under the western Transverse Ranges (south of the San Andreas fault) because that is the dominant direction of vergence of the large folds and thrust faults. In addition, the structural relief progressively increases northward from the Ventura basin. The cross sections of Yeats et al. (1988) are restricted to a narrow area of the Ventura basin and do not consider the bulk of the Transverse Ranges, most of which lie north of the basin. The sections of Yeats et al. (1988) are neither balanced nor provide a restoration. Specific problems consist of a mismatch of hanging-wall and footwall cutoffs, no pinning lines, unrealistic relations between fault and fold shape, and increasing fault slip upsection. Therefore, Yeats et al. (1988) did not present an integrated, restorable, or complete solution of deformation of the western Transverse Ranges. Northward and southward extension and restoration of their cross sections would show their proposed north-vergent Sisar detachment and its linkage to the Oak Ridge fault as untenable.

5. Yeats and Hufnile state that the geometry of thrust ramps north of the Ventura basin shown in our cross section is arbitrary and could be easily modified, affecting convergence calculations. The position and ramp height in our interpretation are based on solving for the observed fold geometry and structural relief of the Lion Mountain anticline, Santa Ynez Range, San Rafael Mountains, and Pine Mountain and are not arbitrary.

6. Yeats and Hufnile state that the only major tectonic event during the Oligocene in the western Transverse Ranges was extensional. There is abundant evidence throughout the western Transverse Ranges and southern Coast Ranges for late Eocene to early Oligocene convergence such as the folds and thrust faults of the San Rafael high (Reed and Hollister, 1936) and Ynezian orogeny (Dibblee, 1982, see Namson, 1987). Late Oligocene and early Miocene extension is also a widespread tectonic event; however, it should not be confused with the earlier compressive event (Davis and Lagee, 1988).

7. Yeats and Hufnile question the usefulness of deformation rates averaged over 2–3 m.y. to earthquake hazard evaluation. This is an open
question; however, the first order of business in analyzing compression is to develop a restorable geometric and kinematic solution. Determining variable deformation rates requires high-quality subsurface data that include seismic reflection data, a unique set of geologic conditions, and application of compressive growth-structure analyses (Medwedeff, 1989).

We feel that this type of analysis is extremely useful. However, Yeats (1988) did not use this approach.

In conclusion, our interpretation is not unique, but it is balanced and admissible. It is a minimum-slip solution for which there are only a few possibilities. On the other hand, Yeats et al.'s (1988) and Yeats's (1988) interpretations are not balanced and are therefore not admissible. In addition, their interpretations are not minimum slip solutions. Therefore, we believe that our interpretation, estimated slip rates, and recurrence intervals are substantially more defensible.

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Comment and Reply on "Did the Iapetus Ocean really exist?"

COMMENT

Clive Burrett, Department of Geology, University of Tasmania, G.P.O. Box 252C, Hobart, Tasmania 7001, Australia

Although one has to agree that the petrological evidence for the Iapetus Ocean is weak, the major argument used by Tuzo Wilson (1966) for the ocean was paleontological. The strong early Paleozoic faunal divide along the axis of the Caledonian orogen, going not only through the Norwegian Caledonides but also through the British Isles and Newfoundland, affecting almost all Cambrian-Ordovician macrofossil groups, is difficult to account for unless Laurentia and Baltica were separated by a wide ocean. The various paleogeographic arguments for the ocean have been summarized many times (e.g., Burrett, 1973, 1980, 1983; Burrett and Richardson, 1980; Cocks and Fortey, 1982; Ross, 1975; Whittington and Hughes, 1972, 1974; Williams, 1976), and need not be repeated here. If the Iapetus was narrow, we would expect to find very similar shallow-water Cambrian-Ordovician faunas in Laurentia and Baltica or in Scotland and Wales. We do not. This interpretation is only "model dependent" in that most groups of early Paleozoic macrofauna had larval viabilities in excess of ten or so days.

The Early Cambrian reconstruction (Mason, 1988, Fig. 3) of the south pole in the west of Greenland is odd considering that most Early Cambrian paleomagnetism from Laurentia indicates a tropical position (see listings in Piper, 1988). I must also object to the name used for the Cadomian terrane covering central England and parts of Belgium and the Netherlands. This terrane appears (see Mason, 1988, Fig. 1) to exclude the type area of the Cadomian orogeny near the town of Cadomus (= modern Caen) in the Armorican massif. This, to me, is similar to erecting a Caledonian terrane and excluding Scotland.

REPLY

Roger Mason, Department of Geological Sciences, University College, Gower Street, London WC1E 6BT, England

I am grateful to Clive Burrett for drawing attention to John Piper's (1988) valuable paleomagnetic data base, which was not available to me when I wrote my paper (Mason, 1988). I also recommend his book summarizing his conclusions from study of the data base (Piper, 1987). Piper came to the remarkable conclusion that there was a major change in the tectonics of Earth about 1000 Ma, when the Proterozoic supercontinent (then located near the South Pole) broke up. It had been a single megacontinent for nearly 1000 m.y. previously. Paleozoic time was