ROLE OF FAULTS IN CALIFORNIA OILFIELDS PTTC FIELD TRIP AUGUST 19, 2004

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INTRODUCTION

This field trip will examine and discuss the role of faults in southern California oil fields. Faults have played an important role in the development of southern California oil fields, with faults having had both direct and indirect influences on their development. Direct influences consist of structural elements like sealing and leaking faults and trap formation, while indirect influences consist of fault-dominated basin development that controls reservoir and source rocks patterns, source rock maturity levels, and oil migration pathways. The field trip has four stops in the western Transverse Ranges of southern California, where we will observe and discuss various types of fault influences: Stop 1-Towsley Canyon, Stop 2-the Honor Rancho gas storage field, Stop 3-the South Mountain oil field, and Stop 4-the Silverthread Area of the Ojai Oil Field (Fig. 1).

Much of this guidebook is taken from Davis, et al. (1996) where the reader will find additional information on the structure, oil fields, and oil source and thermal modeling of the western Transverse Ranges.

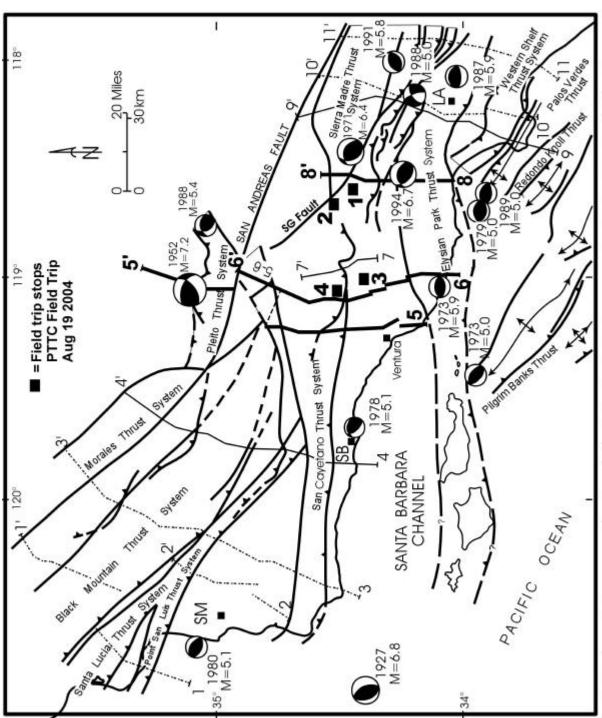
Structural modeling and cross section construction

Several cross sections with deep structural interpretations will be presented and discussed during the field trip (Fig. 1) and it is important that the observer have some idea of the role of structural modeling in making these types of sections. Numerous areas of the southern California lack usable geophysical data for suburface imaging and interpretation. Structural modeling using surface mapping and oil well data can provide testable subsurface interpretations. These interpretations provide a first-order image of the structure and can be combined with even poor quality geophysical data to improve the overall subsurface image. It is important to note that structural modeling can be applied at the regional or oil field scale to improve the subsurface image.

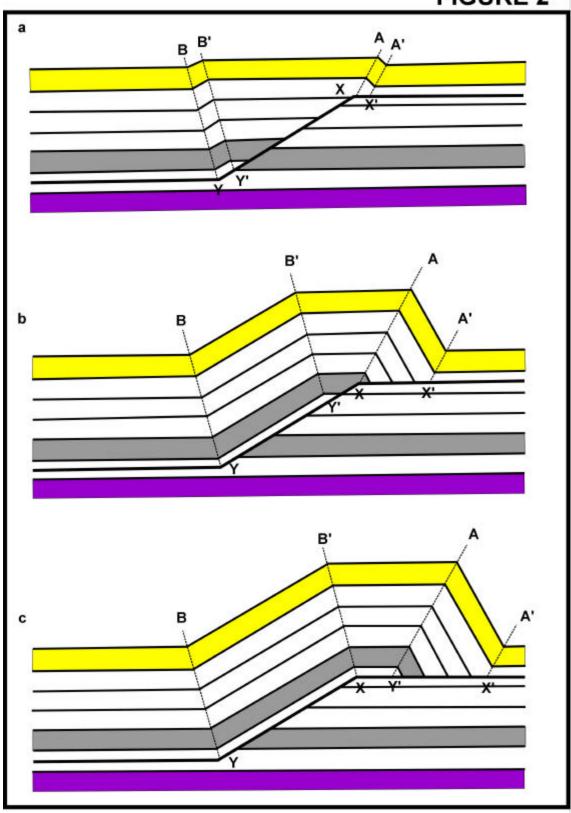
In doing structural modeling in southern California we commonly employed the following: fault-fold modeling, recognition and explanation of structural relief and retrodeformation. Fault-fold modeling is justified in southern California based on empirical data and the understanding of specific map-scale folds, earthquake data, and the success of this technique in predicting subsurface geometry subsequently tested by drilling. Figures 2 and 3 are diagrammatic fault-fold end members that have more complex examples in the field of southern California.

In Figure 4 we show a fault-propagation fold deforming older basin-edge structural relief (normal fault) to explain a commonly observed geometry in many southern California oil fields. Many of these oil fields are anticlinal 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. 4A). During the field trip we will present evidence that these traps are the result of convergent overprinting of older normal faults (Figs. 4B-C) rather than the commonly cited wrench fault style (Fig. 4D).

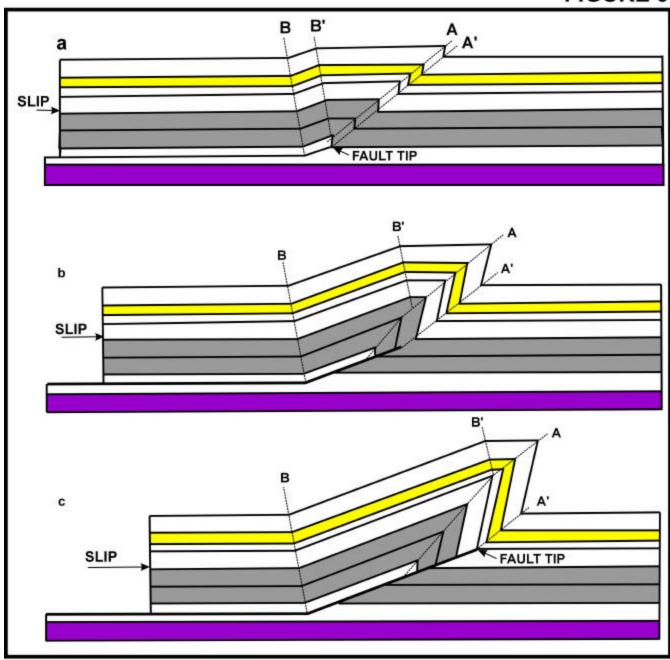
Restoration of cross sections provides a method for testing different structural interpretations. The regional cross sections shown in this guidebook are accompanied by their restorations to pre-convergent time (2-3 Ma). The following article discusses the data, reasoning and interpretation for making the cross section and restoration shown in Figures 5A and 5B.



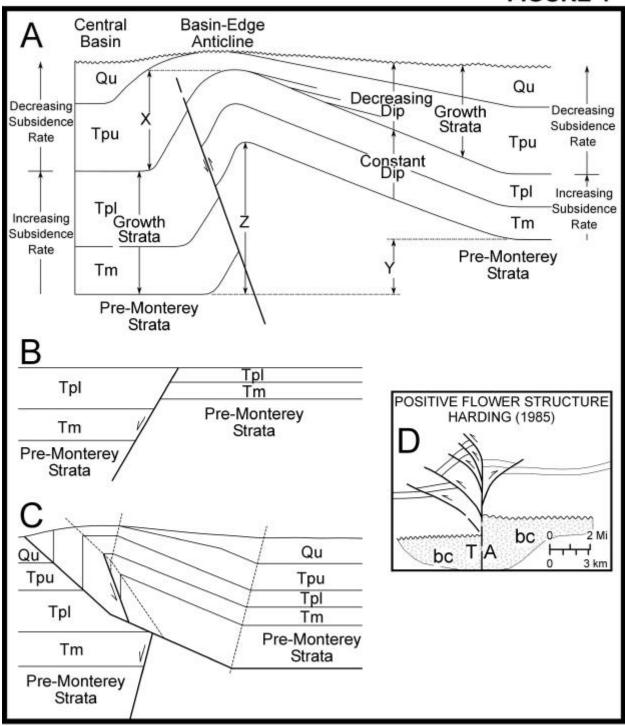
Map of major late Cenozoic thrust ramps of southern California showing destructive compressional earthquakes (modified from Namson and Davis, 1992). Cross section lines 5-5', 6-6', and 8-8' are shown in this guide book; cross section lines 1-1' and 2-2' (Namson and Davis, 1990), lines 3-3', 4-4', 6-6' and 7-7' (Namson and Davis, 1992), an earlier of 8-8' (Davis and Namson, 1994), an earlier version of 9-9' (Davis et al., 1989) and cross sections 10-10', and 11-11' remain unpublished. All cross sections can be downloaded from www.davisnamson.com website.



Schematic progressive development of fault-bend folds as a thrust sheet rides over a step in decollement (Suppe, 1983, 1985)



Schematic progressive development of a fault-propagation fold at the tip of a thrust fault. (Suppe, 1985)



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.

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

(This article is a summary of Namson and Davis (1988b) that explains in a general fashion our interpretation of late Cenozoic convergence in the western Transverse Ranges).

The Transverse Ranges of southern California consist of a series of young, eastwest-trending basement-cored anticlinoria and synclinoria that cut across the northwesttrending structural grain of California. North-south shortening is active and documented by late Pliocene and Quaternary folds convergent faults, geodetically measured northsouth convergence, and numerous compressive earthquake events with north-southdirected 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). 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 highvelocity 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 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. 5A). 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. 5B) 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 (Figs. 5A & B)

On the south the section (Fig. 5A) 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. Subsequent convergence has rotated the upper part of the normal fault to its reverse fault dip.

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 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 Santa Ynez-Topatopa 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 (Fig. 22). The configuration of the Oligocene thrust system is shown in the restoration (Fig. 5B). 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 (Fig. 5A) 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 (Davis and Duebendorfer, 1982, 1987). 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 (Dibblee and Nilsen, 1973). Well data show that the anticlines lie above thrust ramps many of which do not reach the surface. For example, the Wheeler Ridge thrust ramps up across the Miocene sequence to form the Wheeler Ridge anticline, but the thrust never breaks the surface. The splays of the Pleito fault system are shown to root at depth into one common detachment. Isopach mapping in the upper and lower plates of the main Pleito fault shows no evidence for strike-slip motion since Eocene time (Lagoe, 1987).

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

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

Conclusions

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

An important implication of crustal shortening above the mid-crustal detachment is that the lower crust and lithosphere must be shortened or subducted an amount similar to the upper crust. We favor the model of Bird and Rosenstock (1984), in which the lower crust and mantle lithosphere are subducted to account for the shallow-level crustal shortening. The shortening values in this study suggest that a 53-km-long slab of lower crust and lithosphere should have been subducted beneath the western

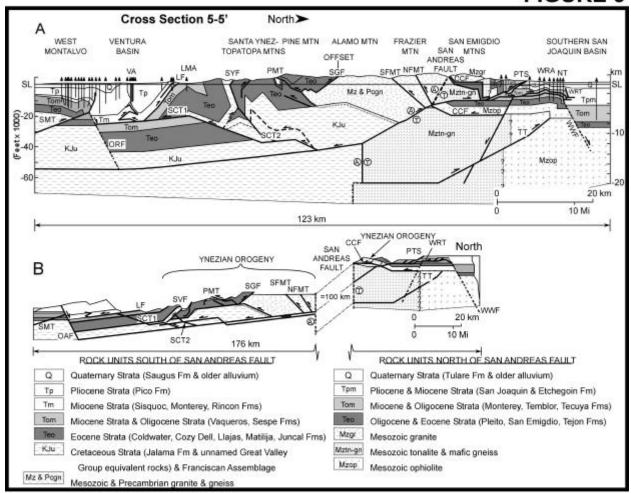
Transverse Ranges during the past 2-3 Ma. The size of the postulated subducted slab compares favorably with the 60-km-thick high-velocity region that dips steeply to a depth of 100-150 km beneath the western Transverse Ranges, observed from seismic tomography (Humphreys et al., 1984).

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 Pliocene to Quaternary folds. The resolution of displacements into orthogonal components is also recognized in the central California Coast Ranges (Namson and Davis, 1988a) and is consistent with the present-day compressive stress field, which is perpendicular to the San Andreas fault (Mount and Suppe, 1987).

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A. Structural transect across the western Transverse Ranges (Namson and Davis, 1988b). CCF=Caballo Canyon fault; LF=Lion Fault; LMA=Lion Mountain anticline; NFMT=North Frazier Mountain thrust; NT=North Tejon oil field; ORF=Oak Ridge Fault; PMT=Pine Mountain thrust; PTS=Pleito thrust system; SCT=San Cayetano thrust (SCT1 and SCT2 are splays); SFMT=South Frazier Mountain thrust; SGF=San Guillermo fault; SMT=South Mountain thrust; SYF=Santa Ynez fault; TT=Tejon thrust; VA=Ventura Avenue anticline; WRA=Wheeler Ridge anticline; WRT=Wheeler Ridge thrust; WWF=White Wolf fault; Circled A and T indicate strike-slip motion of the 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.

Stop 1, Eastern Ventura Basin, Towsley Canyon and the Santa Susana Mountains

Stop 1 is located in the lower part of Towsley Canyon (Ed Davis Regional Park) along the southwest side of Interstate 5 (park at the upper parking area-Fig. 6). We will hike about one kilometer up Towsley Canyon to the core of the Pico anticline. 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 (Fig. 6). 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. The steeply-dipping beds of lower Towsley Canyon belong to the north limb of Pico anticline that lies structurally above the much larger north limb of the Santa Susana Mountains anticlinorium. Davis and Namson (1994) interpret the Santa Susana Mountains anticlinorium to be a crustal scale fault propagation fold and the result of numerous movements on the deep Pico thrust (Fig. 7) that dips southward under the San Fernando Valley.

Surface mapping (Fig. 8) from Winterer and Durham (1962) and a cross section with a number of deep exploration wells drilled along Pico anticline show a number of interesting fault features (Fig. 9). The surface geology of the Towsley Canyon area shows the influence of older subsurface faults on the geometry of the younger convergence. During Miocene and Pliocene time the eastern Ventura basin was a graben between the Oakridge fault system on the west and the San Gabriel fault and an unnamed normal fault on the east (Figs. 8 and 9). During late Pliocene and Quaternary time crustal shortening associated with the growth of the Santa Susana Mountains anticlinorium propagated basinward (northeastward). Well data shows the older normal fault curves to a more northerly strike just north of Towsley Canyon. A similar change is seen in the strike geometry of Pico anticline (Fig. 8), as shown by the surface strike and dips. Changes in the strike geometry of the anticline probably reflect strain accommodation during shortening of the thick sequence of sedimentary rocks against a stronger crystalline basement block to the northeast (Fig. 9).

The influence of older faults on basin inversion seems to be a dominant structural process in this area. Southwest of Towsley Canyon the Santa Susana fault is exposed along the south side and crest of the Santa Susana Mountains, and there the fault surface is nearly horizontal. Under the northeast flank of the Santa Susana Mountains, and above the Oak Ridge fault system, the fault becomes steeply dipping to the northeast (Fig. 9). At greater depth we interpret the fault dip to flatten beneath the Pico anticline and Towsley Canyon. During the late Pliocene and early Quaternary the thickest portion of the eastern Ventura basin was thrust southward over the older fault-controlled basin margin (Oak Ridge fault system) by the Santa Susana fault. Changes in the dip geometry of the Santa Susana fault probably reflect ramping of the fault over the strong block of undifferentiated lower Tertiary and Cretaceous sedimentary rocks south of the Oak Ridge fault system (Fig. 9). Davis and Namson (1994) propose that the Santa Susana fault formed prior to being folded by the Santa Susana Mountains anticlinorium since the north limb of the anticlinorium folds both the hanging wall and footwall of the Santa Susana fault (Figs. 7 and 9).

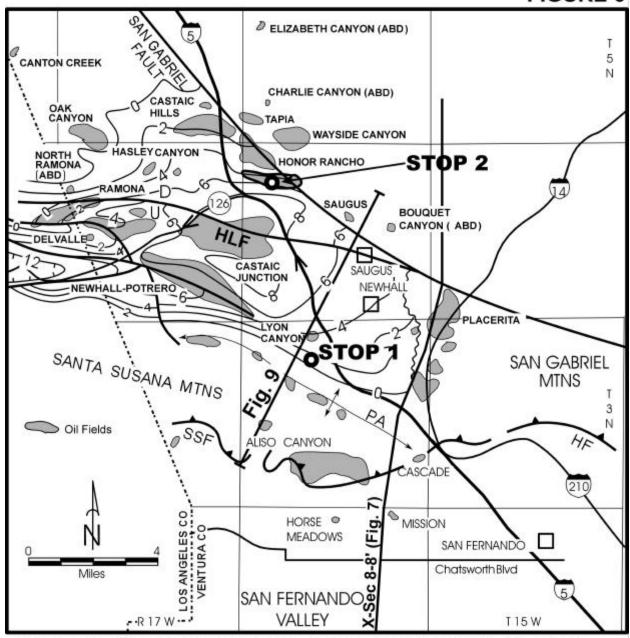
The Aliso Canyon oil field is located in the footwall of the Santa Susana fault (Fig. 9). The Aliso Canyon field is now a gas storage field operated by Southern California Gas Company. The Aliso Canyon field, and basin modeling of the eastern Ventura basin (Davis, et al. 1996) suggest the field was charged with hydrocarbons during basin inversion.

Deep erosion of Towsley Canyon 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 of Stop 1 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 was deposited at outer neritic to bathyal depths, and Winterer and Durham (1962) proposed that this coarse-grained unit is 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 San Gabriel fault. 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. 8) which was the site of some of California's earliest exploration efforts. For instance in 1876, in nearby Pico Canyon, Pacific Coast Oil Company completed California's first commercial oil well.

Stop 1 to Stop 2

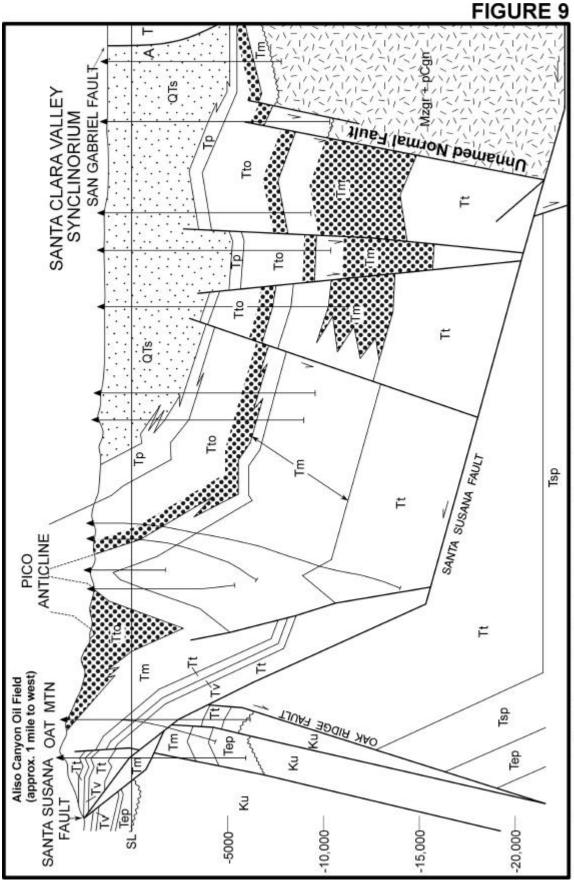
Take Interstate 5 north across the Santa Clara Valley. Exit the interstate at Magic Mountain Parkway and go left, then right along the Old Road. Make a right at Rye Canyon Road and continue northeast to the Honor Rancho gas storage field operated by the Southern California Gas Company.



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; HLF = Holser Fault; PA = Pico Anticline; SSF = Santa Susana Fault.

FIGURE 8 Y68 Subsurface Miocene Normal Faul CANYON Qu PICO 007 (1-5) ₹⁷³ √⁷⁸ **QTs** Y67 Qu Tp QTs TOWSLEY STOP CANYON **QTs** Oil Seeps 20-39° **1-5** 46 Tm **QTs** 45 55 4000 FEET Tp 80°-C CANYON

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, Tt=Towsley Formation, Tp=Pico Formation, QTs=Saugus Formation, Qu=undifferentiated alluvial strata.



Cross section across the Santa Susana Mountains showing inversion of the eastern Ventura basin. Abbreviations: Mzgr + pCgn=Mesozoic granitic rocks and Precambrian granite and gneiss, Ku=upper Cretaceous strata, Tep=undifferentiated Paleocene and Eocene strata, Tt=Topanga Fm; Tv=Topanga Fm igneous unit, Tm=Modelo Formation, Tto=Towsley Formation, QTs=Saugus Formation.

Stop 2, Honor Rancho Gas Storage Field and the Eastern Ventura Basin

Stop 2 is in the Honor Ranch gas storage field that is operated by Southern California Gas Company (Fig. 10). The Honor Rancho gas storage field is located in the eastern portion of the Ventura basin; a highly deformed Tertiary age marine basin within the Transverse Ranges of southern California. The deepest part of the eastern Ventura basin occurs just west of the storage field and the intersection of Highway 126 and Interstate 5 (Fig. 6). The surface geology around the storage field consists of southwest dipping beds of the nonmarine Quaternary age Saugus Formation (Fig. 10). The San Gabriel fault, a major fault of southern California (Crowell, 1952), occurs just northeast of the storage field and separates the mostly marine eastern Ventura basin on the west from the mostly nonmarine Soledad basin on the east.

At the Honor Rancho field natural gas is stored in the Wayside 13 sand that was the oil reservoir for the Southeast Area of the Honor Rancho oil field (DOG, 1974). The Wayside 13 sand is the basal unit of the Towsley Formation-an upper Miocene to lower Pliocene sequence of deep water deposited shale and turbidite sand that was observed at Stop 1. Several hundred exploratory and development wells have been drilled in the Honor Rancho field, adjacent oil fields and the surrounding area. These wells provide much of the subsurface data for structural mapping and three-dimensional (3D) structural imaging of the storage reservoir (Davis and Kuncir, 2004). Steep surface dips and other factors such as surface noise have prevented the acquisition of useful seismic reflection data at the Honor Rancho field. In lieu of useful seismic imaging, we have constructed a digital 3D structural model of the storage field using Seismic MicroTechnology's Kingdom Suite (SMT) for well log correlation and basic subsurface mapping and Paradigm's GeoSec program for structural modeling. Figure 11 is a structure contour map on the top of the Wayside 13 sand from the digital model using the SMT software. The map shows that migrating and stored hydrocarbons are sealed up dip by a down-to-the-north normal fault. The normal fault appears to be a growth fault active during Towsley deposition, and along this fault shale dominated middle and upper parts of the Towsley Formation are faulted against the Wayside 13 sand providing an excellent up dip seal. However, the nature and exact location of the east and west lateral seals remain problematic.

Regional and local cross sections (Figs. 12A and B) provide additional information on the geologic setting, structural geometry, petroleum system of the Honor Rancho gas storage field. The gas storage zone (Wayside 13 sand) lies in the footwall block of the late Pliocene and Quaternary age Honor Rancho thrust. This thrust is younger and overlies the up dip trapping normal fault described above. The gas storage field lies in the hanging wall of the F-1 reverse fault and this fault is probably responsible for the general structure of the gas storage field. Both the Honor Rancho thrust and the F-1 reverse fault strike east-west and intersect the older San Gabriel fault just to the east of the storage field. The Honor Rancho thrust fault and F-1 reverse fault probably continue westward as blind faults beneath the north side of the Ventura basin and connect with the San Cayetano fault system that we will observe and discuss at Stop 4.

Southwest of the storage field is the trough of the eastern Ventura basin where organic-rich shale of the Modelo Formation (upper Monterey Formation equivalent) provides a mature source for oil in the basin (Davis, et al.,1996). Southwest of the trough are the Castaic Junction and Newhall Potrero oil fields that are trapped by late Pliocene and Quaternary anticlines along the southwest margin of the eastern Ventura basin (Fig. 12A)

Summary of the Honor Rancho Gas Storage Field Mark Kuncir Southern California Gas Company

Discovery and Primary Production

Honor Rancho Storage Field is located in Valencia, near the intersection of Interstate Highway 5 and State Highway 126 in the northwest part of Los Angeles County (Fig. 10). Before being converted to gas storage, the field was known as the Southeast Area of the Honor Rancho Oil Field. The Southeast Area was discovered by ChevronTexaco in May 1956 with the completion of test well "Honor Rancho 'A' (NCT-2)" #13 (API 037-07605), that flowed at a rate of 1,101 barrels per day (BPD) of 37.3 degree gravity oil and 1,260 MCF of gas. The well was completed in the Wayside 13 sand, which was encountered at a depth of approximately 10,000 feet and had initial reservoir pressure of 4411 psig.

From 1956 until 1975, ChevronTexaco drilled 23 wells at the field and nearly all of the wells completed initially produced 1,000 BPD of oil. The reservoir operated under solution-gas expansion with gravity drainage and a weak water drive. The proven area of the field was 310 acres and the initial oil/water contact was at –9,700 feet TVD. The original oil in place (OOIP), estimated by material balance was 35 MMB. By 1976, cumulative oil production was 15.4 MMSTB, a recovery of 43 % of the OOIP.

Gas Storage

The Southern California Gas Company acquired the Southeast Area from ChevronTexaco in 1975 and converted the field to gas storage and renamed it the Honor Ranch Storage Field. There are now 38 wells completed to the storage zone (Wayside 13 sand): 23 combination injection-withdrawal wells, 8 withdrawal-only wells, and 7 oil wells equipped with gas lift (Note that WEZU-13A is completed outside the storage zone, and WEZU-C4 is currently plugged-back and idle). All of the wells acquired from ChevronTexaco were reworked, and 17 combination injection-withdrawal wells were drilled by Southern California Gas Company. Each well is equipped with a wellhead safety shutdown system and lateral piping that can be used to kill the well remotely.

Injection and Withdrawal

In an effort to maximize oil production at the field in 2002-2003, wet-gas wells were given the highest priority for withdrawal. As demand for deliverability increased, the dry gas wells located higher on the structure were utilized. Honor Rancho's deliverability is

currently 1.00 BCF/day down to a working-gas inventory of 5.0 BCF, and is limited by the capacity of the surface facilities and transmission lines. During periods of injection, the majority of the gas was injected in wells located in the gas cap in an effort to sweep the fluid in the reservoir down structure toward the oil production wells. In 2002, 23.4 BCF of gas was withdrawn and 20.51 BCF was injected at Honor Rancho. As of September 2003, 13.11 BCF has been produced and 18.28 BCF has been injected.

Fluid Production

A total of 107,759 BO and 281,403 BW were produced in 2002 from the 7 oil wells completed in the Wayside 13 storage zone and the average GOR and water cut were 217 MCF/BBL and 72%, respectively. As of September 2003, 46,571 BO and 227,516 BW were produced, and the cumulative volume of oil produced from the Wayside 13 sand is 19.6 MMBO. This is a recovery of 56% of the estimated OOIP. Wells WEZU-23, 25 and C5A were flowing throughout most of 2002 and 2003. These wells were only put on gas-lift when the reservoir pressure was too low (<7.9 BCF working inventory). The other oil wells at the field were on production during periods of withdrawal or when the total volumes of recycle gas was less than 30 MMCFD (economic limit). WEZU-13A is a stripper well that is completed outside of the storage zone, is equipped with a rod-pump, and is on a timer.

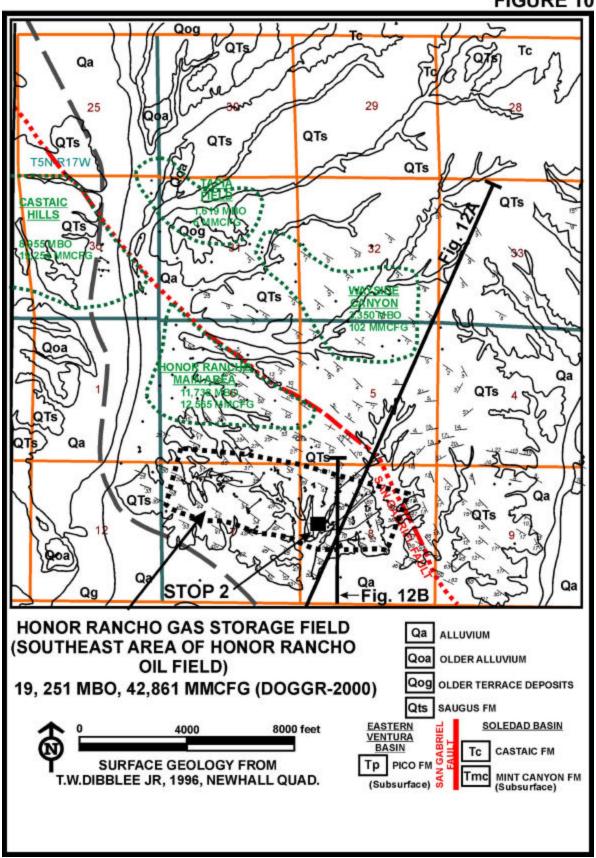
Brine Disposal

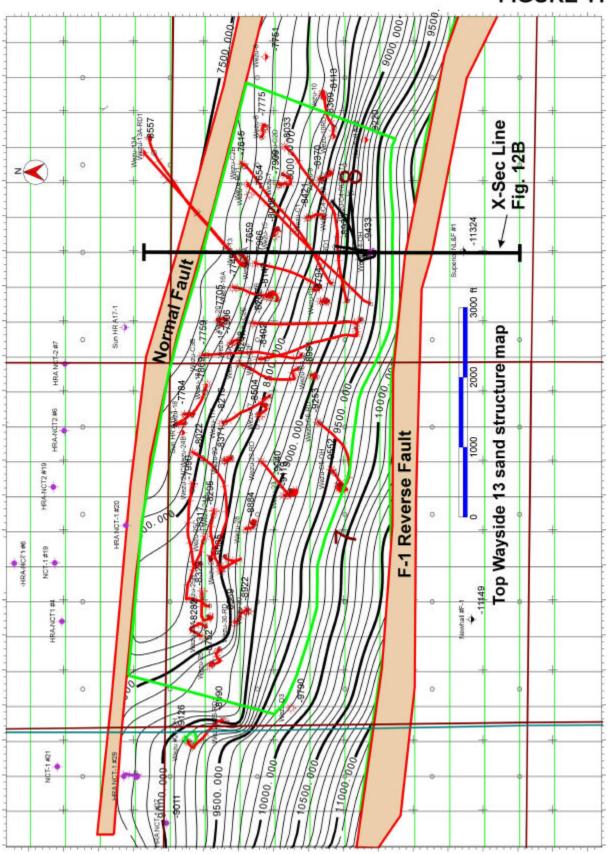
Well WEZU-BD1 is completed to the lower Pico disposal zone in the lowermost part of the Pico Formation and is the only active brine disposal well at Honor Rancho. The well was drilled in 1988 and was completed within the thickest part of the lower Pico disposal zone. Structurally, the disposal zone ranges in depth from greater than 6,000 feet subsea to less than 1,000 feet subsea, and slopes southward. The disposal zone does not reach the surface within the area of Honor Rancho field, nor does this zone contain any fresh water aquifers as identified from electric logs and drilling reports.

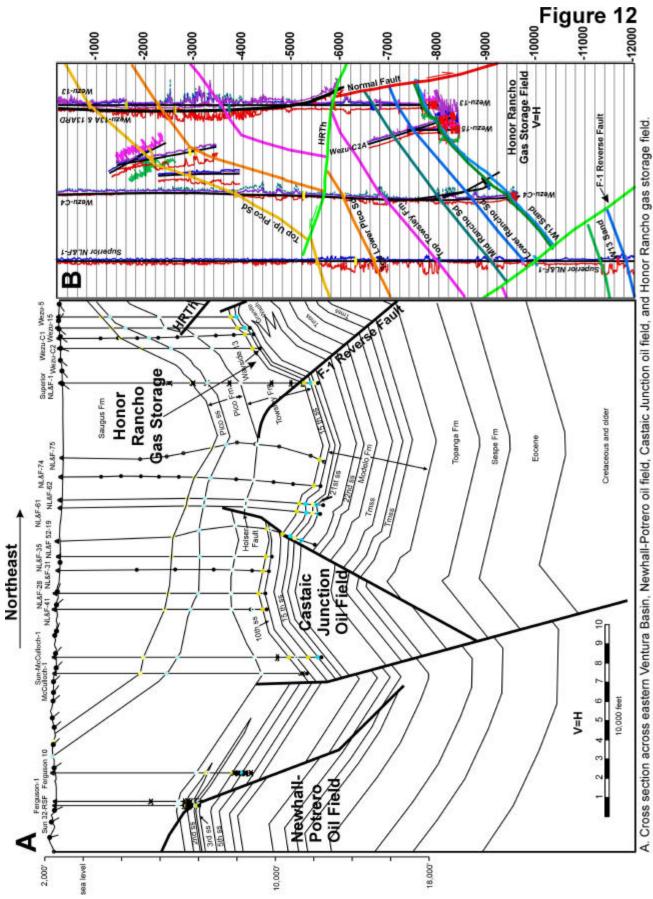
Water injection into the lower Pico disposal zone at Honor Rancho began in 1989. Thus far, approximately 3.5 MMBW has been injected into WEZU-BD1. In 2002 and 2003, 500,369 BW were injected in the well at an average rate of 936 BWPD at 957-psig-injection pressure. The current shut-in wellhead pressure is 300-psig.

Stop 2 to Stop 3.

Return to Magic Mountain Parkway and go west, make a right at the Old Road and go north for approximately 1 mile. Make a left on the on-ramp of the west bound Highway 126. Continue westward on Highway 126 to Santa Paula and exit highway at Highway 150. Connect southward with the South Mountain Road and cross the Santa Clara River and continue east to the entrance of the South Mountain oil field. Turn right and drive up steep hill to the oil field office-Stop 3 is a short walk to the west of the office.







A. Cross section across eastern Ventura Basin, Newhall-Potrero oil field, Castaic Junction oil field, and Honor Rancho gas storage field. B. Cross section across Honor Rancho gas storage field. HRTh = Honor Rancho Thrust

Stop 3, Central Ventura Basin and South Mountain Oil Field

The South Mountain oil field is trapped along the Oak Ridge fault trend (Figs. 13 and 14). The crest of the South Mountain anticline is well exposed in a large ravine just west of Stop 3. 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 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 that is underlain by the east-west trending Ventura basin (Fig. 15). 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 Ventura basin are shown in Figures 16A, B and C (Stop 3 is located near cross section B-B'). All three cross sections have structural styles in common that include the north-verging asymmetric anticline of the Oak Ridge-Montalvo trend that is separated from the Ventura basin by a steep south-dipping Oak Ridge fault. The structural interpretation in the three cross sections shows the Oak Ridge fault as 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 South Mountain anticline. Figure 17 is a kinematic model showing the interaction between an older normal fault and a younger fault-propagation fold, and this model illustrates the structural evolution of the Oak Ridge fault and South Mountain anticline.

The Ventura basin petroleum system is in many ways similar to the system in the southern San Joaquin basin and other petroleum basins of southern California (Davis, et al, 1996): 1) The Monterey Formation is the main source rock for both basins but the unit is immature in the oil fields of both basins. 2) South Mountain oil field is bounded on the north by a deep fault bounded basin (Fig. 15) analogous to the Tejon depocenter of the southern San Joaquin basin. 3) The deep Ventura basin is generating oil today at great depths in a rapidly subsiding depocenter similar to the Tejon depocenter. 4) At South Mountain oil is migrating into a Quaternary age anticline similar to the Wheeler Ridge anticline of the southern San Joaquin basin. Oil generation in the Monterey Formation began only about 2 Ma in the deep Ventura basin, and maturity modeling and biomarker data suggest that the Monterey Formation is not mature enough to generate gas and this may explain the lack of free gas at South Mountain and the other oil fields in the central Ventura basin.

Summary of South Mountain Oil Field Modified from Gregory J. Cavette

(in Davis, et al. 1996) Nuevo Energy Company Santa Maria, CA

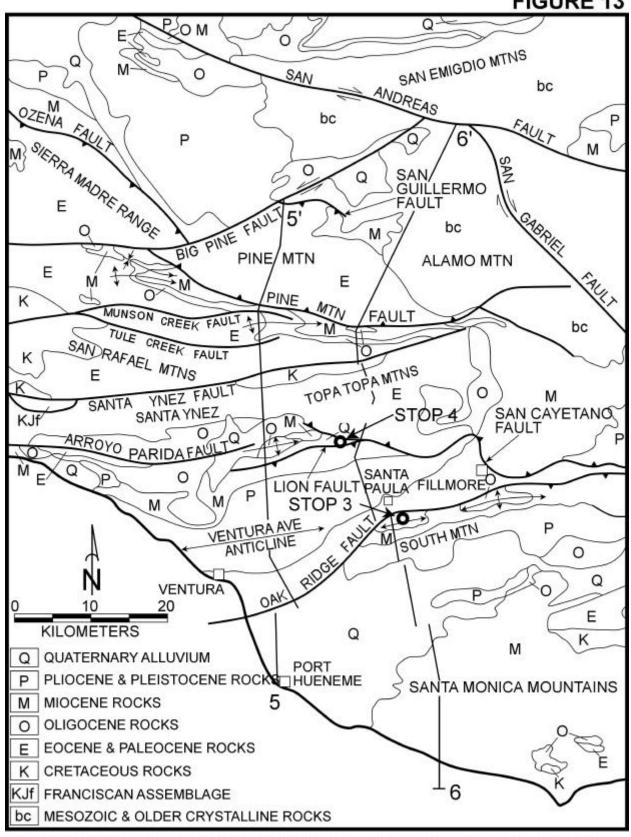
The South Mountain oil field was discovered in 1915 by the Oak Ridge Oil Company "South Mountain" #1 well, drilled to a depth of about 900 m with cable tools. Initial production was about 25 BOPD of 25° oil with no water cut from selected intervals between 455 to 900 m. The Main Area is an anticlinal trap along the upthrown side of the Oak Ridge reverse fault (Figs. 18 and 19). 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, as of 1996, is 106 MMBO (18° to 22° API) and 215 BCFG.

The Bridge Pool area of the South Mountain field 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, as of 1996, from the Bridge Pool is 44 MMBO (30° to 36° API) and 88 BCFG.

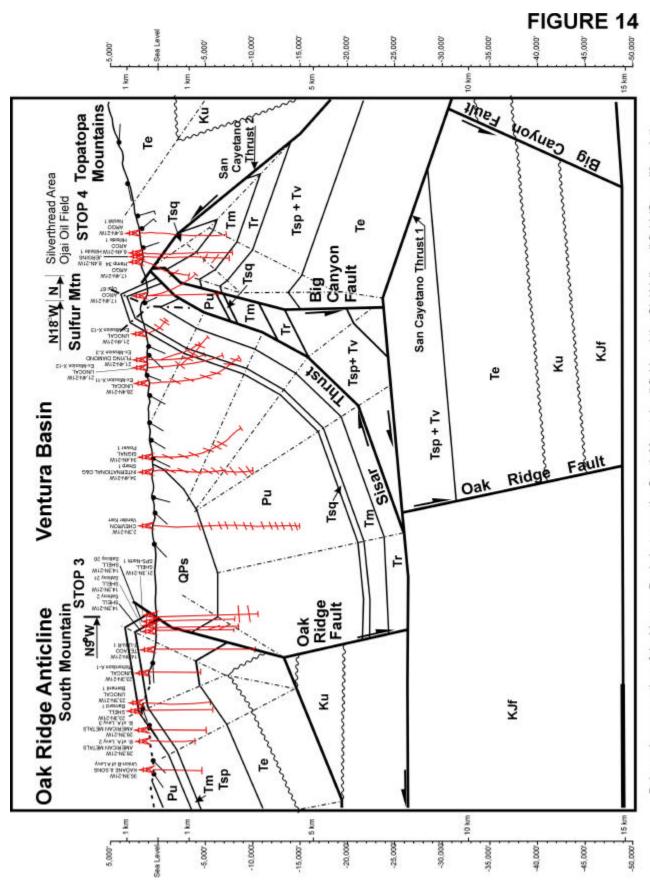
The DOGGR (2002) reports that cumulative oil and gas production for all of the South Mountain oil field is 155.3 MMBO and 309.7BCFG

Stop 3 to Stop 4.

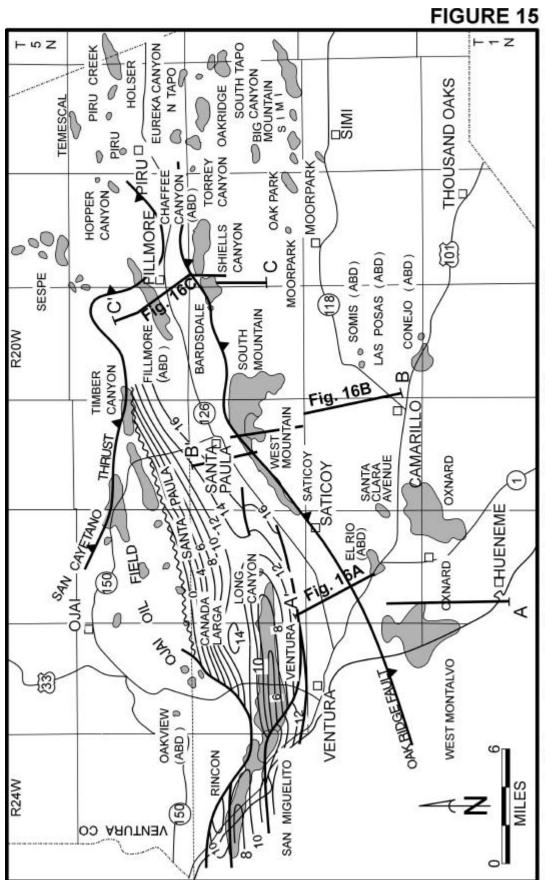
Return to Santa Paula via the South Mountain Road. Connect with Highway 150 in Santa Paula and go north. The highway will parallel Santa Paula Creek and then bend sharply to the west just north of Sulfur Mountain. Take the Silverthread oil field road on the right.



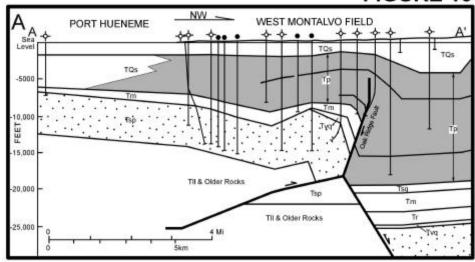
Map showing field trip stops and major surface faults of the central portion of the western Transverse Ranges.

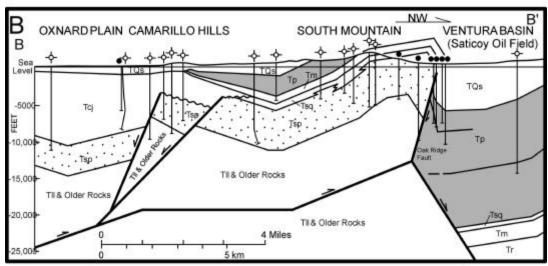


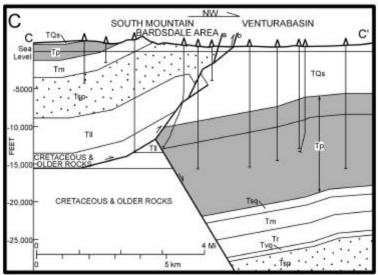
Balanced cross section of the Ventura Basin between the South Mountain oil field and the Ojai Valley oil field (Stops #3 and 4).



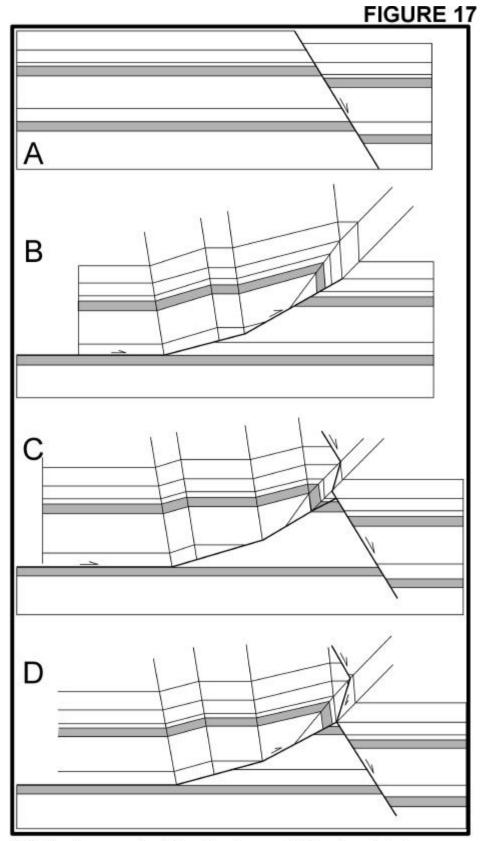
Structure contour and oil field map of the western Ventura Basin (modified from Hindle et al., 1991 and DOG, 1974). Contours on base of Pico Fm; thousands of feet



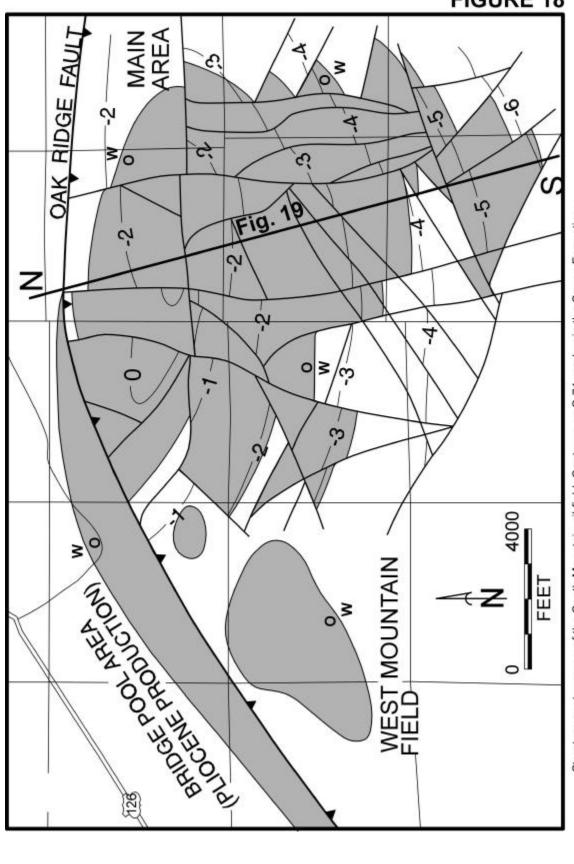




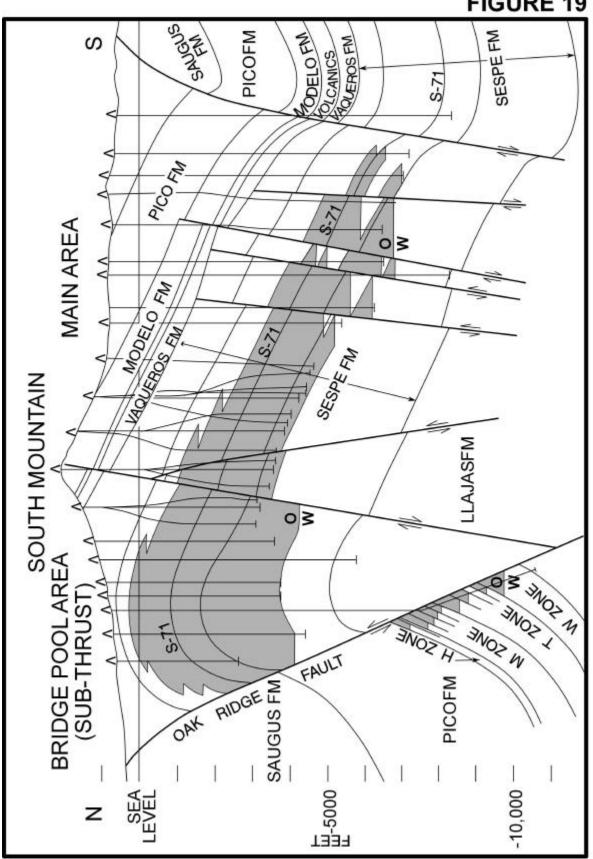
Cross section A-A' through the Oak Ridge-Montalvo trend near the Montalvo oil field. Cross section B-B' through the Oak Ridge-Montalvo trend near the South Mountain oil field. Cross section C-C' through the Oak Ridge-Montalvo trend near the Bardsdale area.



Model showing progressive deformation of a normal fault and growth strata by a fault-propogation fold.



Structure contour map of the South Mountain oil field. Contours on S-71 marker in the Sespe Formation.



Cross section across the South Mountain oil field and the Oak Ridge fault showing oil traps and producing zones.

Stop 4, Silverthread Area, Ojai Valley Oil Field

Stop 4 is located just east of Upper Ojai Valley where we will view the complex structural setting of the Ojai Valley oil field (Fig. 20). We will walk a short distance to view the San Cayetano thrust which is one of the most important faults of the Western Transverse Ranges and is responsible for the uplift of the Santa Ynez–Topatopa Mountains (Dibblee, 1982). In this location the San Cayetano thrust has emplaced the Eocene age Coldwater Formation over the Miocene-age Monterey and Pliocene-age Pico Formations. There is complex folding and faulting observed at the surface caused by several regional faults that include the San Cayetano thrust, Sisar thrust and Big Canyon fault.

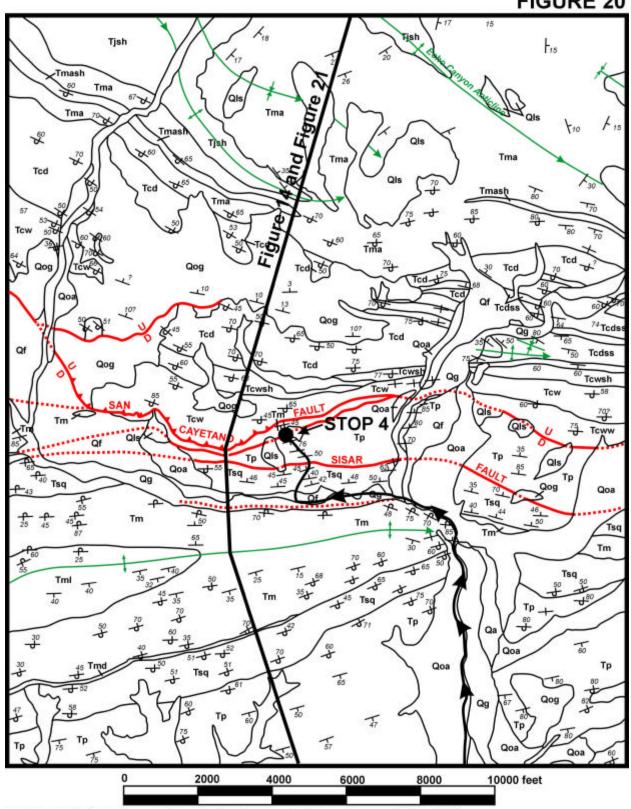
The surface geology and subsurface well information of the area are integrated into a cross section shown in Figure 14. Stop 4 is just east of the cross section line and along trend of the complex structure where the San Cayetano thrust, Sisar thrust and Big Canyon fault occur near the surface. The cross section interpretation shows that the San Cayetano thrust is separated into two splays. San Cayetano thrust 2 is the splay that occurs at the surface and emplaces Eocene age rocks (Te) over the Miocene and Pliocene age rocks (Pu, Tsq, Tm). San Cayetano thrust 1 is interpreted in the deep subsurface to form the large fault-bend fold anticline with the front limb observed along the north side of the Ventura basin. Regionally, this "blind thrust" portion of the San Cayetano thrust is very important. It is the cause of the uplift of the Santa Ynez Mountains and folding along the north side of the Santa Barbara Channel from this location west to Point Conception.

The Sisar thrust is a north-verging thrust with an asymmetric anticline in the hanging wall. It is interpreted to be a back-thrust of the San Cayetano thrust system that consumes slip of the deep blind thrust splay. The hanging wall anticline making Sulfur Mountain is interpreted to be a fault-propagation fold.

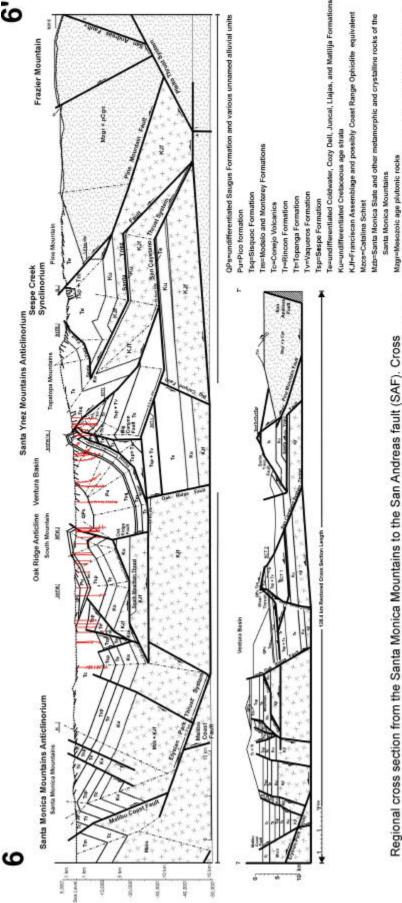
The Big Canyon fault is defined mostly from subsurface data and is interpreted to be a high-angle Pliocene-age normal fault that was down to the south on the northern margin of the Pliocene-age Ventura basin. The Big Canyon fault has been cut, translated and rotated in the hanging wall of the San Cayetano thrust 1. The undeformed original geometry is shown in the lower left corner of the cross section.

Much of the oil production from the Ojai Valley oil field is from the footwalls of the Sisar and San Cayetano thrust 2 on either side of the Big Canyon Fault. It is clear that the faults as well as folds play an important role in the traps that form the oil fields. Oil was first discovered in the Silverthread Area in the 1860's by prospectors drilling along the oil seeps that are present along the trace of the San Cayetano thrust (Mitchell, 1969). The productive limits of the Silverthread Area (210 acres) were realized by about 1920 and commerical production stabilized at near 45 BOPD from the late 1930's to the late 1960's (Mitchell, 1969). Subsequently production was increased and in 2002 production was 614.3 BOPD and 1,809.7 MCFD (DOGGR, 2002). Productive intervals are sands within the Saugus Formation, the Big Canyon fault zone, and sands and fractures within the Monterey Formation. Wells completed in the Saugus Formation or the Big Canyon fault are usually less than 1,000 feet deep and produce roughly equal amounts of water and oil. Cumulative production, as of 2002, was about 18.8 MMBO

and 36 BCFG with the majority of production was from intervals in the Monterey Formation (DOGGR, 2002).

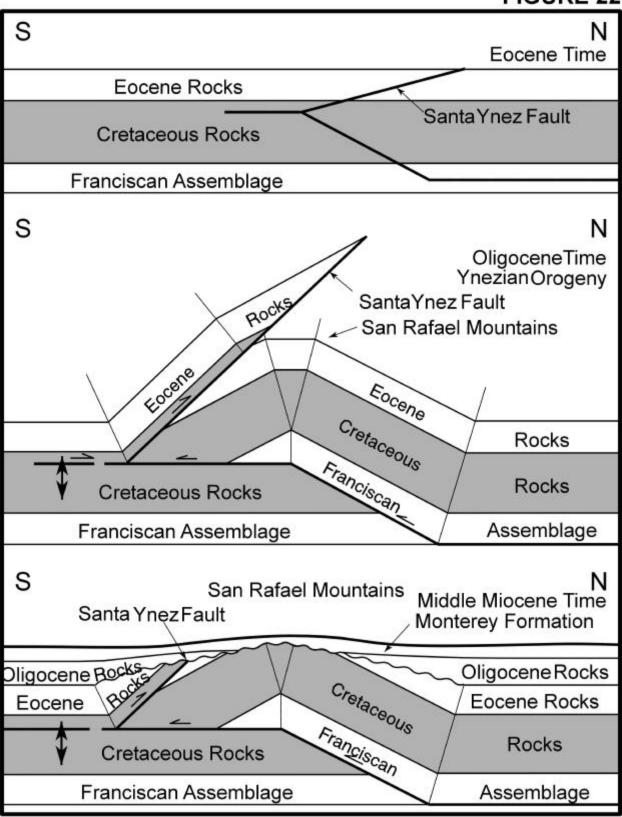


Surface geologic map of a portion of the Santa Paula Peak Quadrangle (Dibblee, 1990).



Regional cross section from the Santa Monica Mountains to the San Andreas fault (SAF). 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.

pCgn=Precambrian and possibly younger high temperature me



Model illustrating the late Eocene to Oligocene deformation of the San Rafael Mountains and Santa Ynez fault (Namson 1987)

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