# Ventura Basin Oil Fields: Structural Setting and Petroleum System

Leaders: Thom Davis, Jay Namson, and Stuart Gordon
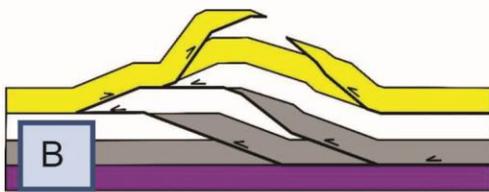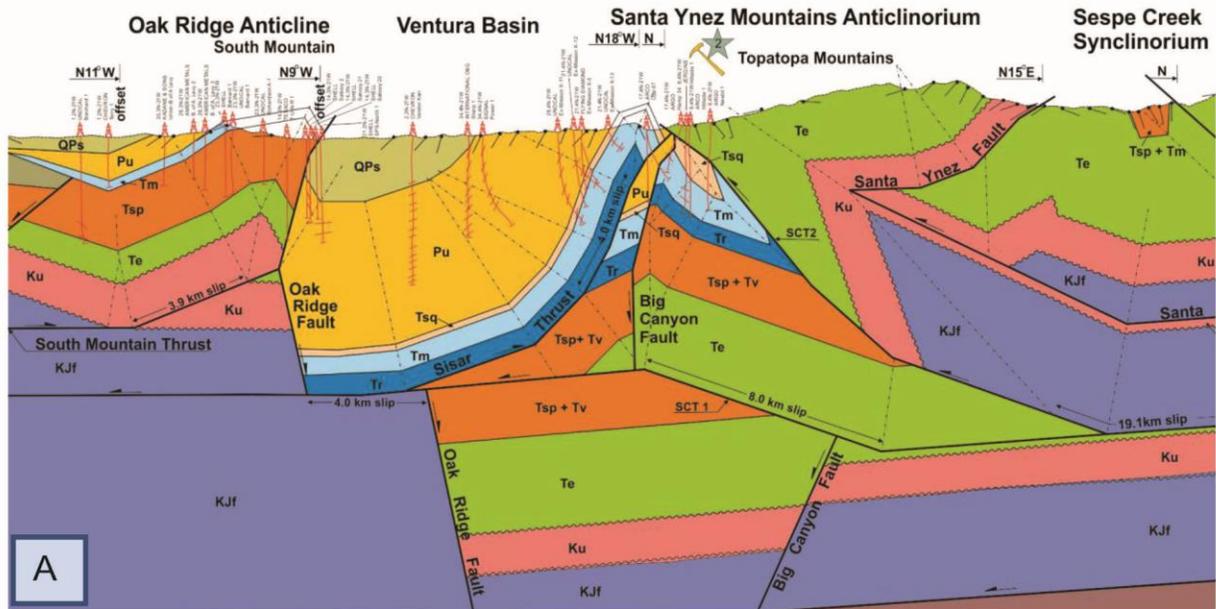
A, Portion of Namson's 1991 deep interpretation of the Ventura basin between the Oak Ridge anticlinal trend and the Sespe Creek synclinorium (cross section 7-7'). Field trip Stop #2 is in the Silverthread area of Ojai oil field and near surface trace of the upper splay of San Cayetano thrust fault. B, Imbricated thrust wedge model that is applicable to deformed area between Sisar and San Cayetano fault. C, Cross section of the Silverthread area of the Ojai oil field. D, Structural evolution of the Santa Ynez fault (Namson, 1987).
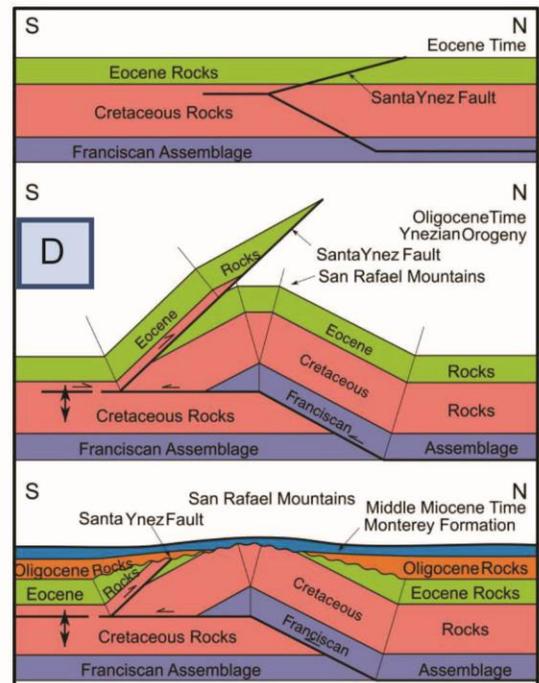
Ventura Basin Oil Fields:
Structural Setting and Petroleum System

Field Trip #5, May 7, 2015

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Guidebook for Field Trip #5

May 7, 2015, 7:30 AM-5:30 PM, meet at hotel entrance at 7:15 AM

Joint Annual Meeting of PSAAPG & Coast Geologic Society, PSSEPM, & PCSSEG Field trip sponsor:

Coast Geological Society

Location: Embassy Suites Mandalay Beach Hotel and Resort,

2101 Mandalay Beach Road, Oxnard, CA 93050, May 2-8, 2015

Stop 1, Aliso Canyon gas storage field, and possibly Oat Mountain.
Stop 2, Silverthread Area of the Ojai oil field.
Stop 3, Ojai Valley overview.
Stop 4, Ventura oil field, and return to hotel.

Field trip summary and instructions: Field Trip #5 will stop at the Aliso Canyon oil field (now a Southern California Gas Company gas storage field), if time allows the top of Oat Mountain, the Silverthread Area of the Ojai oil field (a California Resource Corporation oil field), the Ojai Valley, and the Ventura oil field (Figure 1). We will drive through the AERA operated Ventura oil field on public roads and make a brief and final stop outside the oil field property. Stop presentations will emphasize the geometry, kinematic development, and timing of the structural hydrocarbon traps. We will focus on our interpretation of how the map-scale structures (and traps) are linked geometrically and kinematically across the basin, and the influence of structural development on the local petroleum system. Stops will involve very short hikes (<several hundred feet) or no hiking. Participants need to wear long pants and boots, due to poison oak and entering two active oil and gas fields, and participants need to bring a hardhat.

Welcome to our field trip, Thom Davis, Jay Namson, Stuart Gordon

Figure 1. Map of southern California showing petroleum basins, oil fields, San Andreas fault, regional cross section lines by Namson and Davis that are posted online, and the four Ventura basin stops for this field trip. All cross sections are available for viewing and downloading at www.thomasldavisgeologist.com, and www.davisnamson.com.

Introduction

This field trip is a structural and petroleum system overview of the prolific Ventura oil basin of southern California (Figure. 1). The field trip will emphasize some of the key structural and petroleum system features of the basin and the field trip leader's interpretations. During the last three decades Jay Namson and Thom Davis have used balanced cross sections and fault-related fold models, constrained by surface mapping, oil well data, and 2D seismic reflection data, to build new interpretations of the regional structure and hydrocarbon trapping mechanisms in southern and central California; including the Ventura basin (Davis and Namson, 1986; Namson, 1987; Namson and Davis, 1988b, 1991, and 1992; Davis, et al, 1996). This effort started initially in the late 1970's with Davis' PhD work in the San Emigdio Mountains and detailed mapping of the western Big Bend of the San Andreas fault to better understand the fault's relationship to the nearby convergent structures (Davis, 1983; 1987). During the early 1980's Namson and Davis worked for the Atlantic-Richfield Company (ARCO) and were involved in the deep exploration drilling effort in the Caliente Range and Carrizo Plain of the Cuyama basin. Namson's expertise in balanced cross sections and fold and thrust belts outside of California profoundly changed ARCO's approach to exploring in California including the Ventura basin. Concurrently Namson and Davis recognized that the commonly used and cited flower-structure model (Wilcox, et al., 1973; Harding, 1976, 1985; Sylvester, 1988) did not account for the structural geometry and kinematic development of structures shown by drilling, detailed surface mapping, and 2D seismic reflection in the Caliente Range (Davis, et al., 1988). In contrast these data showed the Caliente Range was a small fold and thrust belt adjacent to the San Andreas fault. The faults and folds are the result of convergence with little or no strike-slip despite the close proximity of the San Andreas fault. The range is an inverted portion of the Cuyama basin with substantial subthrust areas yet to be explored!

Following the 1983 Coalinga earthquake Namson and Davis showed that the deformed west-side of the San Joaquin basin could be interpreted as a northeast-directed structural wedge that is being driven into the undeformed basin, and balanced cross sections and fault-fold models could be used for seismic risk evaluation of blind thrust faults (Namson and Davis, 1988a, b; Davis et al., 1989). In 1983 the Coalinga earthquake perplexed much of academic seismological community, the United States Geological Survey (USGS), and the California Division of Mines and Geology (CDMG) with its lack of surface rupture from an earthquake

with a M>6.0 and its main shock slip solution of pure convergence on a low angle fault plane located near and dipping towards the San Andreas fault. With the exception of Bob Yeats' work in the Ventura basin the geologists and seismologists involved in seismic risk evaluation at that time relied solely on surface geology or observations in very shallow trenches across faults. They did not use publically available subsurface data from oil and gas wells, or appreciate the relationship between folding and thrust faulting, and the possibility of "blind" thrust faults.

Subsequently Davis and Namson were involved with the USGS funded NEHRP program and the early days of the SCEC (Southern California Earthquake Center) and constructed additional cross sections and published papers on active thrust faults in southern and central California (Figure 1). Funding and the work flow were inconsistent, and in general the academic community were not that excited about a couple of "oil company" geologists with a new approach to seismic risk evaluation, a new structural model for active convergence in southern California, or working in areas such as the Ventura basin and competing for funding with academics already established in these areas. As a result most of the cross sections and interpretations presented here were done from the mid-1980's through the mid-1990's with minor changes made in the subsequent years.

We believe our interpretations have stood the test of time and criticism. Other workers in the Ventura basin that were so critical of our work in publication and public forums, stating our cross sections have "little value in estimating seismic risk" and "less in accord with available data than other solutions" (for instance: Yeats and Huftile, 1989-reprinted at the end of this guidebook), have subsequently published interpretations that have evolved over time to more closely resemble our original work (compare the cross sections in Namson, 1986, 1987; Namson and Davis, 1989b; Namson and Davis, 1991, 1992 to the sections of Yeats, et al., 1988; Huftile and Yeats, 1995).

Figure 1 shows some of the regional cross sections done by us nearly three decades ago and are available for downloading (at no cost) from www:thomasldavisgeologist.com. Over time we have changed the cross section numbers as we have added cross sections, and some of our older publications and reports will show different label numbers than what are shown in Figure 1. For the Ventura basin, what is now labeled cross section 6-6' was 5-5' in Namson

and Davis (1991), what is now cross section 7-7' was 6-6' in Namson and Davis (1991), and what is now cross section 8-8' was cross section 7-7' in Namson and Davis (1991).

To better predict oil and gas distribution resulting from the improved structural understanding, Davis, et al. (1996) undertook 1-D geohistory modeling using ARCO's (now ZetaWare's) Genesis software. The petroleum system analysis (Magoon and Dow, 1994) and burial history modeling presented here and supported by geochemical data show that oil generation only recently began (1-3 Ma), which provides us with a unique view of an active petroleum system in an actively deforming region.

Transpression: The Ventura basin is located in the western Transverse Ranges and not far from the San Andreas transform fault, and structural models of transpression have an important role in understanding hydrocarbon field trapping and its relationship to structural development of the basin. The San Andreas fault through much of southern California is oblique to the plate motion between North America and the Pacific plates, and two transpressive models have been used to explain the strain response to the stress field: 1) the more commonly cited wrench model that results from a strong San Andreas fault (Wilcox, et al., 1977; Harding, 1976; 1985; Sylvester, 1988), and 2) strain-partitioning along a weak San Andreas fault that is characterized by pure strike-slip, and a coeval fold and thrust belt with the faults located away from the San Andreas fault showing no, or little, evidence of strike-slip motion (Mount and Suppe, 1987; Zoback, et al., 1987; Townend and Zoback, 2004). Wrench faulting in transpressional settings is characterized by distinctive petroleum traps and geometric and kinematic structures: en echelon folds and footwall blocks that provide hydrocarbon trap closure, oblique-slip reverse-faults that steepen with depth and merge with a master strike-slip fault that produces a fault and fold geometry called flower structures. However, we believe that a better model for petroleum geology, seismic risk evaluation, and the late Cenozoic structural geology of southern California is strain partitioning with the development of fold and thrust belt and coeval strike-slip motion along the San Andreas fault. Specifically these data show fault-ramp induced folds, thrust and reverse faults with little or no strike-slip movement, and fault surfaces that flatten with depth. These convergent faults do not steepen with depth into the San Andreas fault but rather have listric-shaped fault surfaces and must intersect the San Andreas fault at a high angle, and translate and deform the shallow San Andreas fault from its deeper crustal location (Namson and Davis, 1988a, b).
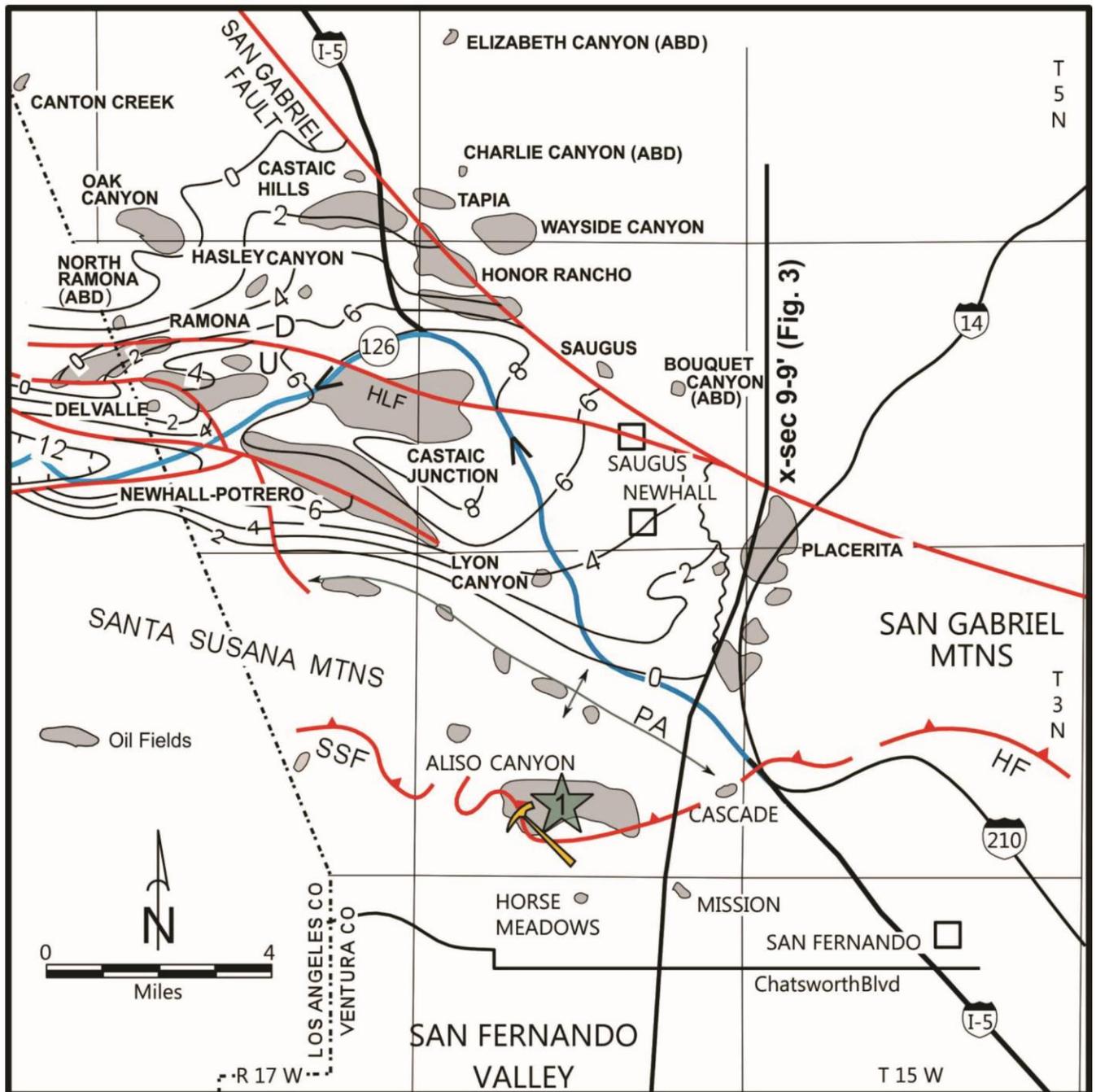
Figure 2. Eastern Ventura basin structure map. Structure contour and oil field map of the eastern Ventura basin (modified from Hindle et al., 1991, and DOGGR,1992). Contours on top of Modelo Formation (Monterey Formation equivalent). Abbreviations: HF = Hospital fault; HLF = Holser fault; PA = Pico anticline; SSF = Santa Susana fault. Map shows that present area of deepest Monterey Formation burial is between Honor Rancho and Newhall Potrero oil fields and some distance north of Aliso Canyon and Stop #1. Blue line with arrows shows route of the field trip after leaving Stop #1 and along I-5 and Hwy 126.

Directions to Stop #1: From the Embassy Suites Mandalay Beach Hotel and Resort take Harbor Blvd southeast where it merges with Channel Islands Blvd (stay to left), from Channel Island Blvd make a left onto Victoria Ave. Take Victoria north to the 101 Freeway and go south on freeway through Camarillo, Newbury Park, and Thousand Oaks to the 23 Freeway. Take the 23 Freeway north towards Moorpark, and 23 Freeway will merge and bend eastward into the 118 Freeway. Proceed east on the 118 Freeway through Simi Valley to the northern San Fernando Valley and exit 118 Freeway at Tampa Ave. Take Tampa Ave north (left) to end of Tampa and turn left on Sesnon Blvd, then make a right into entrance of Southern California Gas Company's Aliso Canyon Gas Storage Field. Follow the Limekiln Canyon road into the gas storage field. Our stop is along the upper drainage of Aliso Canyon.

Stop #1, Aliso Canyon Gas Storage Field, Oat Mountain, and the eastern Ventura basin

Geologic summary: The Aliso Canyon oil field lies along the south flank of Oat Mountain in the eastern portion of the Santa Susana Mountains (Figure 2). Here the southeastern portion of the Ventura basin is shortened by folding and convergent faults with resulting uplift and deep erosion that exposes the Miocene, Pliocene, and early Quaternary age basinal trough, aka "basin inversion." Regional cross 9-9' (Figure 3) shows the position of the Aliso Canyon field with respect to the nearby major structural elements of southern California: Santa Monica Mountains anticlinorium and the Elysian Park thrust, San Fernando Valley synclinorium, Santa Susana fault, the Santa Susana Mountains and eastern Ventura basin, the San Gabriel fault, and the nonmarine Soledad basin. The small cross section inset shown in Figure 3 is Davis and Namson's (1994) interpretation of the cause of the 1994 Northridge earthquake (M=6.7) along the Pico thrust. Oat Mountain was uplifted about one meter during the earthquake on the Pico thrust. Davis and Namson (1994) propose that the Santa Susana fault formed prior to being folded northward by the deep north limb of the deep Santa Susana Mountains anticlinorium. The anticlinorium lies beneath the Santa Susana Mountains and the northern half of the San Fernando Valley and the north limb of the anticlinorium folds both the hanging wall and footwall of the Santa Susana fault.

The surface geology at the Aliso Canyon field consists of mostly folded and faulted Miocene and Pliocene age marine strata and nonmarine Quaternary strata of the southeastern Ventura basin (Figure 4). Upper Cretaceous through Eocene strata are exposed in the hills to the

southwest of Aliso Canyon and 17,000 feet of composite section of upper Cretaceous through Quaternary section are on the surface or penetrated by wells in the area of Aliso Canyon (Lant, 1977). The north-dipping Santa Susana fault reaches the surface near the topographic break between the Santa Susana Mountains and the northern margin of the San Fernando Valley (Figure 4). Much of what is known about the structure of the Aliso Canyon field (Figure 5) and surrounding area is from oil well data as the geometry of much of subsurface is hidden by the hanging wall sheet of the Santa Susana fault (Dibblee x-sec A-A' shown in Figure 4). Usable seismic reflection images do not exist and subsurface interpretations are based on well data, cross sections, and structural modeling. Lant's 1977 cross sections nicely show the complex geology below the Santa Susana thrust sheet (Figures 6A & B). Lant's dip section (Figure 6A) show that the Santa Susana fault consists of two splays that dip gently northward and then steepen below the south limb of Oat Mountain syncline. This area is so complex that differences remain in the interpretation of the surface geology: Dibblee shows the Santa Susana thrust with a structural window in the hanging wall in the upper Aliso Canyon drainage (Figure 4) while Lant does not show this window in his field mapping or cross sections (Figure 6A & B). The hanging wall of the Santa Susana fault consists of the thickest portion of the eastern Ventura basin that was thrust southward over the basin margin by the Santa Susana fault. Lant's and Dibblee's cross sections show the complex nature of the footwall block of the Aliso Canyon gas storage field that is located between the Santa Susana thrust and the Frew fault (Figures 6A, 7A-D). The Frew fault and the deeper Ward fault are south-dipping reverse faults that cut across a thick Pliocene age section that is mapped as Pico Formation and belongs to the southern margin of the eastern Ventura basin. Below the thick Pliocene section is a thin section of Modelo Formation (Monterey Formation equivalent) that rests unconformably on Cretaceous through Eocene age strata with the Topanga Formation missing. From these relationships Lant (1977) concluded that the Aliso Canyon field lies within a structural shelf along the southern margin of the eastern Ventura basin. Later in the field trip we will discuss the northwest continuation of the southern margin of the Ventura basin and whether key structural elements found at Aliso Canyon can be mapped into the central Ventura basin.
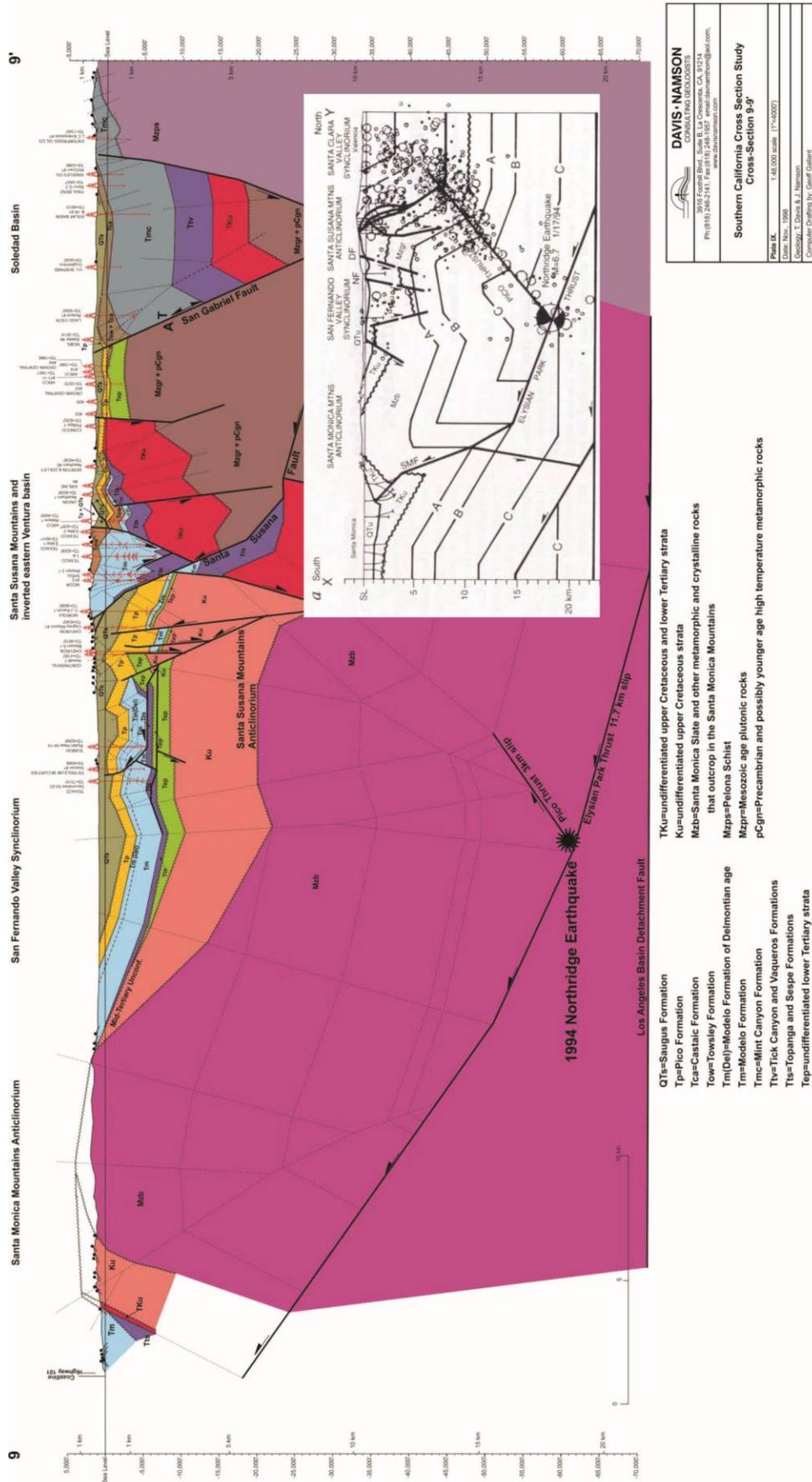
Figure 3. Regional cross section 9-9' from the Santa Monica Mountains anticlinorium to the San Gabriel fault shows inverted eastern Ventura basin and hypocenter for the 1994 Northridge earthquake that occurred on the Pico thrust fault. Cross section inset shows focal mechanism and aftershock distribution from the Northridge earthquake. Shallower aftershocks are the result of fold growth (flexural-slip faults) and propagation of the fold hinge into the Santa Clara synclinorium. Thick black lines show faults, wavy lines show unconformities. Both cross sections also show the Santa Susana Mountains and Santa Monica Mountains anticlinoria as crustal-scale fault-propagation folds above the Pico and Elysian Park thrusts, respectively (Davis et al., 1989, Davis and Namson, 1994). Oil and gas wells are shown with drill holes, and long-short dashed lines are fold hinges. High-angled faults are older Miocene- and Pliocene-age normal faults that formed before regional convergence. Abbreviations on inset: NF, Northridge Hills fault; DF, Devonshire fault; FF, Frew fault; SSF, Santa Susana fault; SMF, Santa Monica fault. QTu, Upper Pliocene and Quaternary rocks; TKu, Lower Pliocene to Upper Cretaceous rocks; Mzcs, Catalina Schist; Mzb, Mesozoic rocks; Mzgr, Mesozoic age granite, A, B, and C, form lines showing Late Cenozoic convergent structure in the undifferentiated crystalline basement.
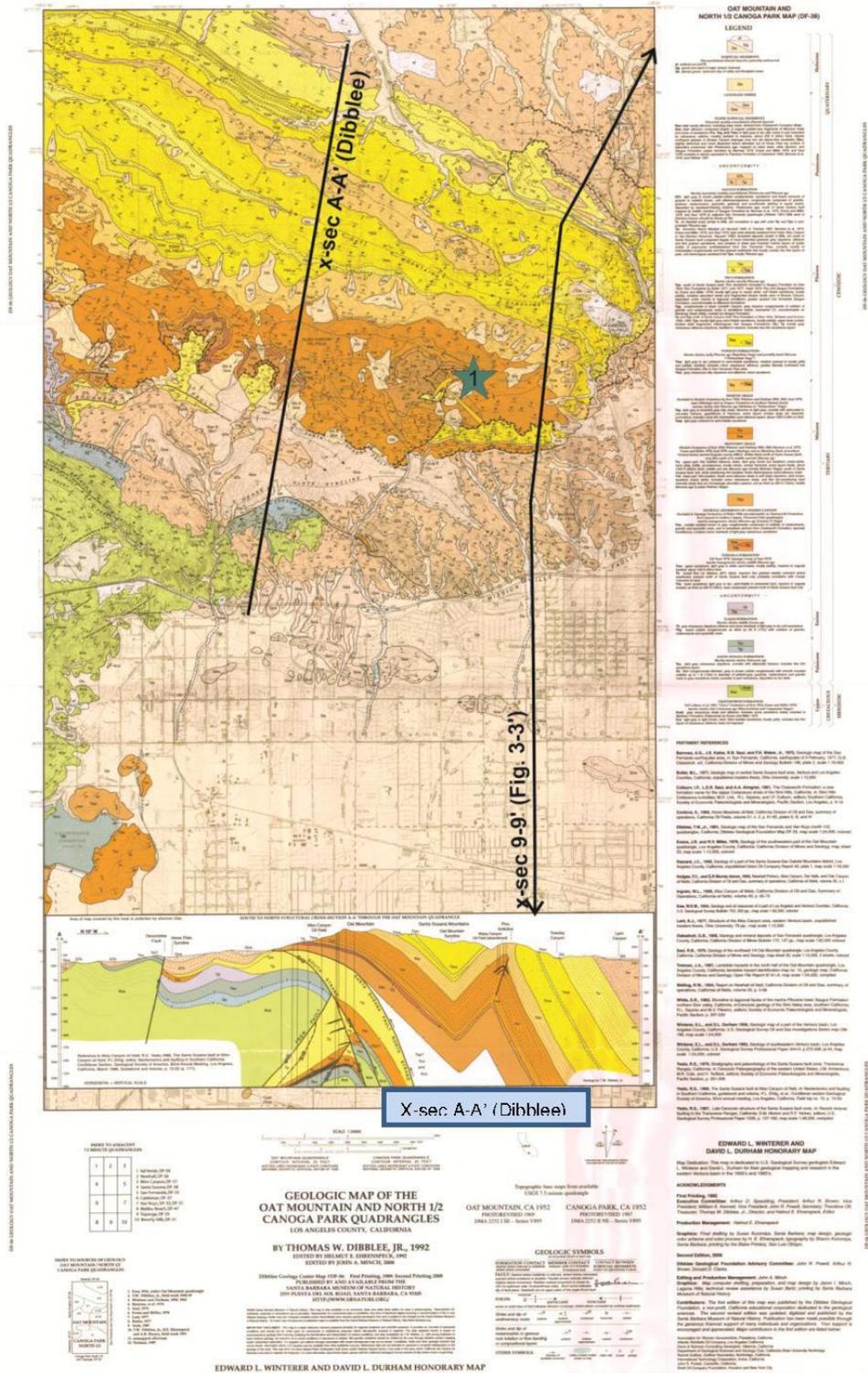
Figure 4. Surface geologic map of the Oat Mtn and Canoga Park (N2) 7.5' quadrangles by
T.W.Dibblee Jr. Paper Dibblee maps are available for purchase from the Santa Barbara Museum
of Natural History: www.sbnature.org/dibblee/. Regional cross section 9-9' is shown in Figure 3.
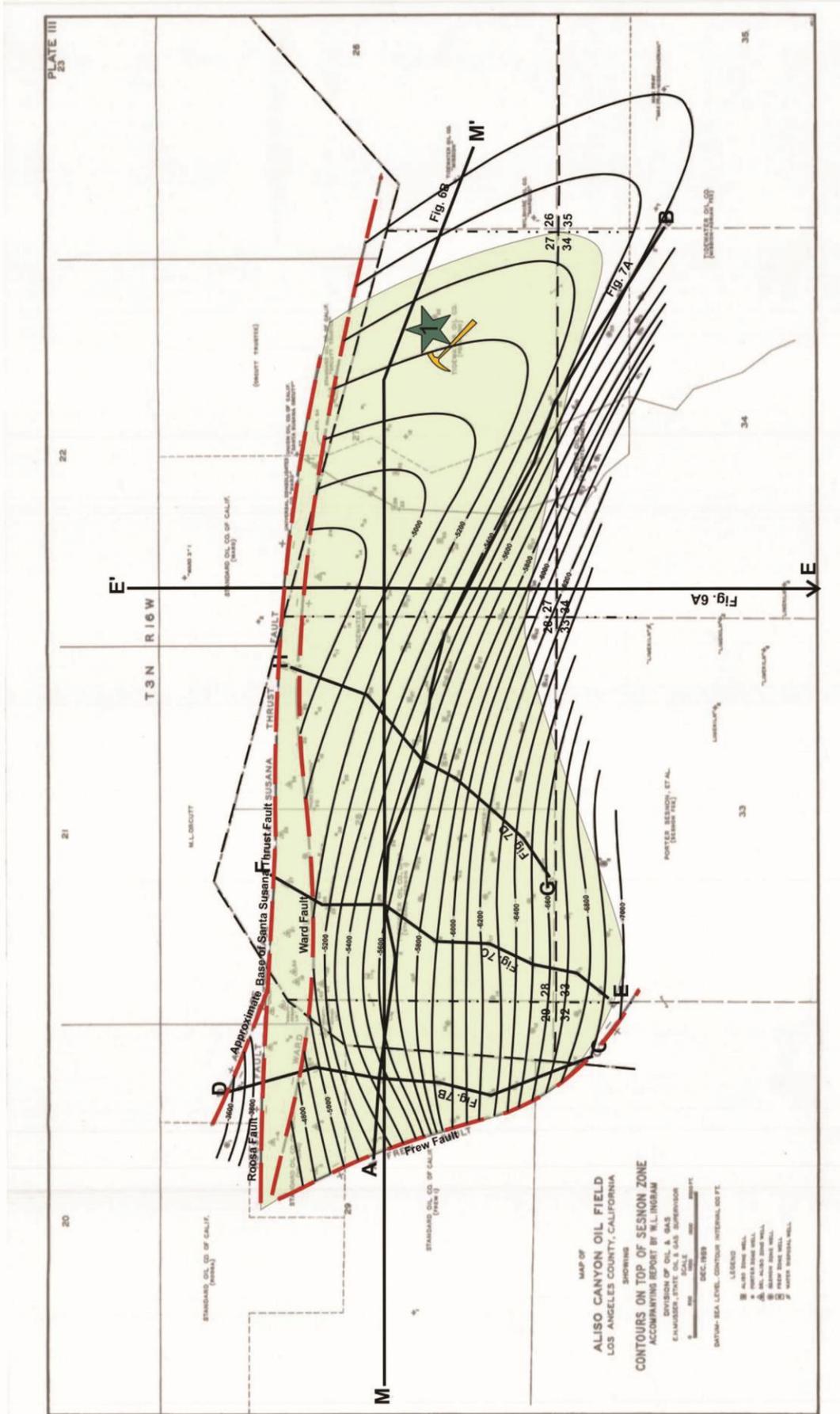
Figure 5. Structure map of the Sesnon zone at Aliso Canyon oil field (Ingram, 1959). Map shows the Sesnon reservoir trap is a faulted anticline with up dip closure provided by the Ward fault, west closure by the Frew fault, and east closure by anticlinal plunge. Wells north of the Ward fault are producing from the shallower Pliocene age reservoirs and trapped up dip by the Santa Susana fault. Cross sections lines A–B, C–D, E–F, and G–H are shown in Figures 7A-D (from Ingram,1959). Cross sections E-E' and M-M' are shown in Figures 6A and 6B (from Lant, 1977).
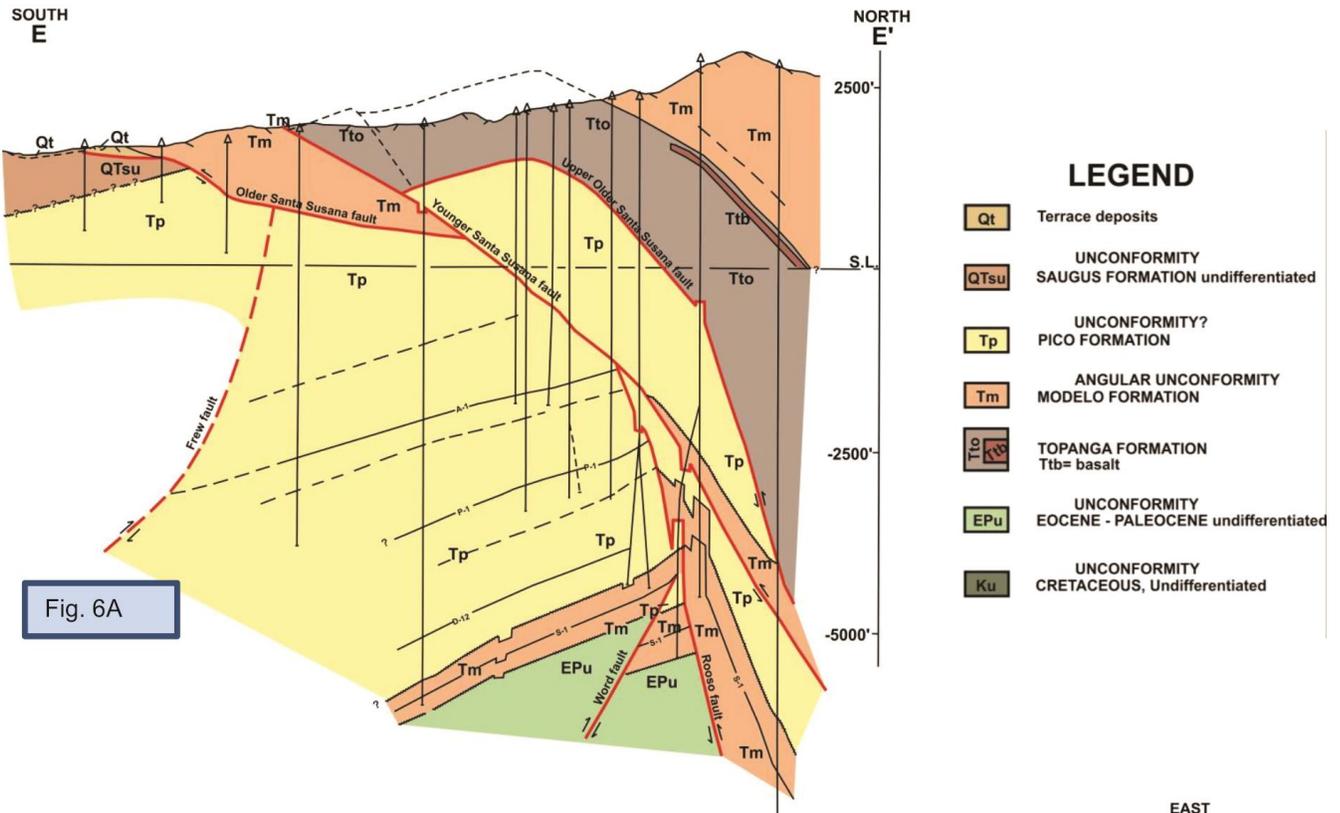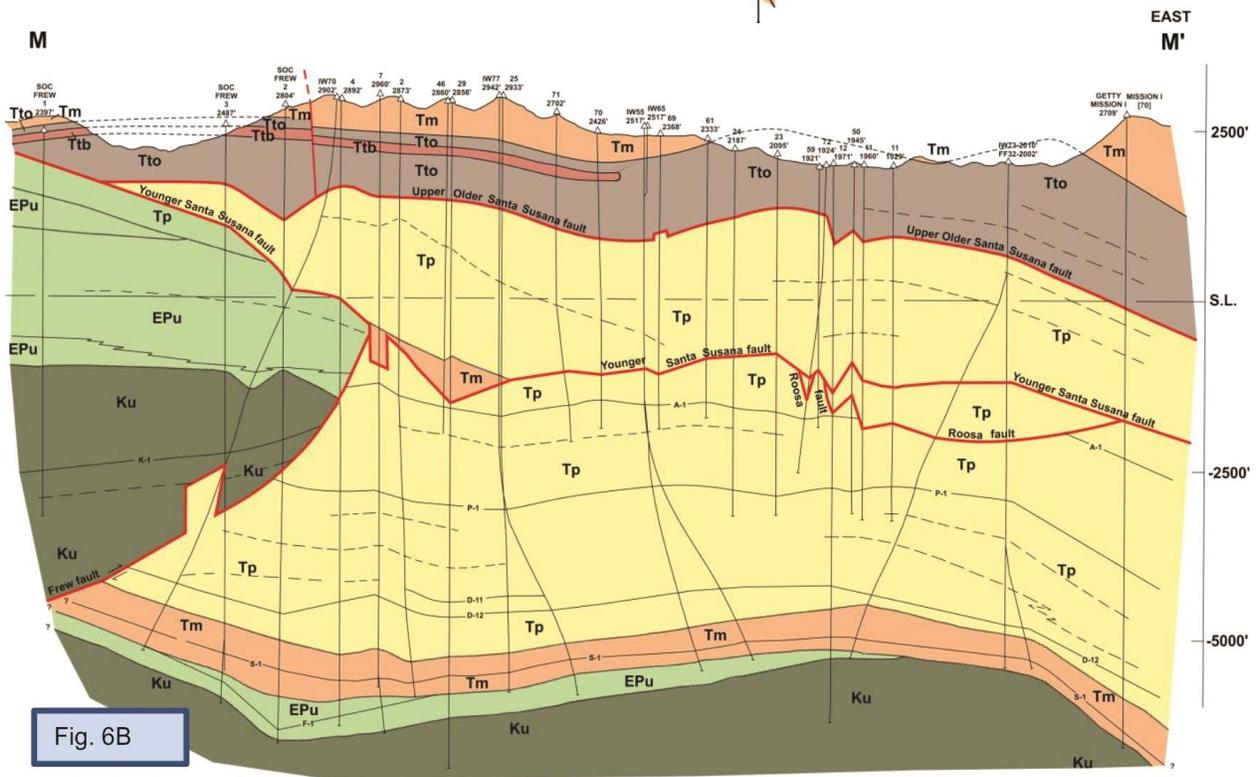
Figure 6A. Dip cross section E-E' of the Aliso Canyon oil field (modified from Lant, 1977).   Figure 6B. Strike cross section M-M' (modified from Lant, 1977). Note the thick Pico Formation section in the footwall of the Santa Susana fault, and the thick Topanga and Monterey Formations section in the hanging wall of the Santa Susana fault. Lant's sections also show that the Santa Susana fault consists of two strands with the younger strand offsetting and folding the older and higher strand.

Figures 7A-D. Cross sections of Aliso Canyon oil field showing e-log curves, key reservoir units, and trapping faults (Ingram, 1959). 7A shows west closure by Frew fault and pinchout of the Porter zone to the east. 7B shows Del Aliso zones trapped by the Roosa fault, a narrow fault block of Sesnon zone trapped by the Santa Susana fault, and the Frew zone eroded by the basal Sesnon unconformity. 7C shows up dip traps formed by the Santa Susana and Ward faults, the Frew zone eroded by the basal Sesnon unconformity, and the oil and gas accumulations that are not shown in other cross sections (DOGGR, 1992). 7D shows up-dip traps formed by the Santa Susana and Ward faults.
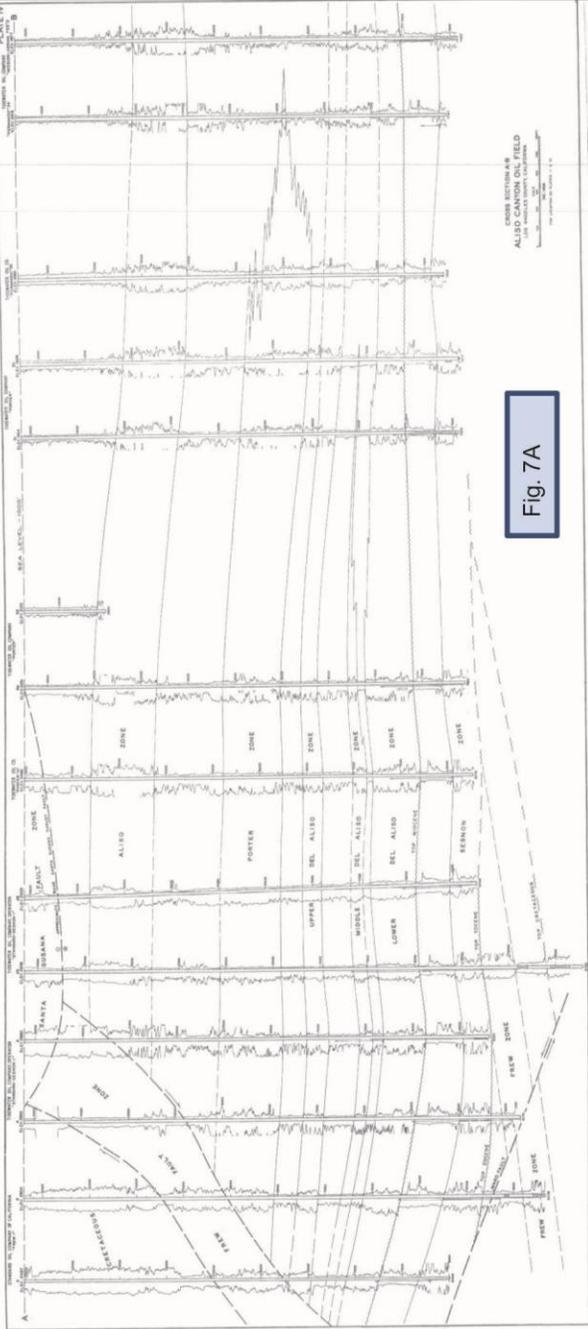
Fig. 7A
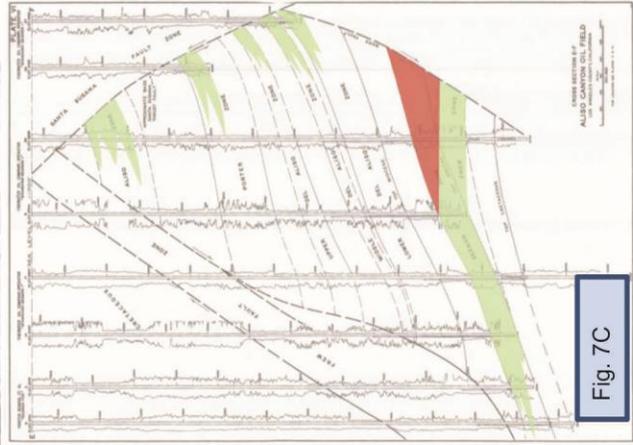
Fig. 7B

Fig. 7C
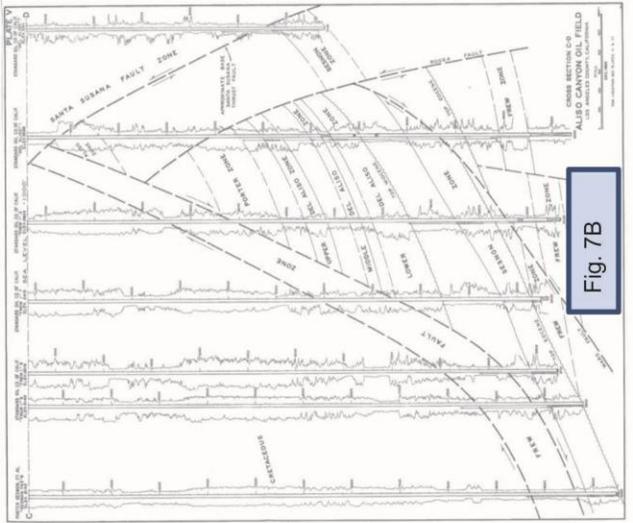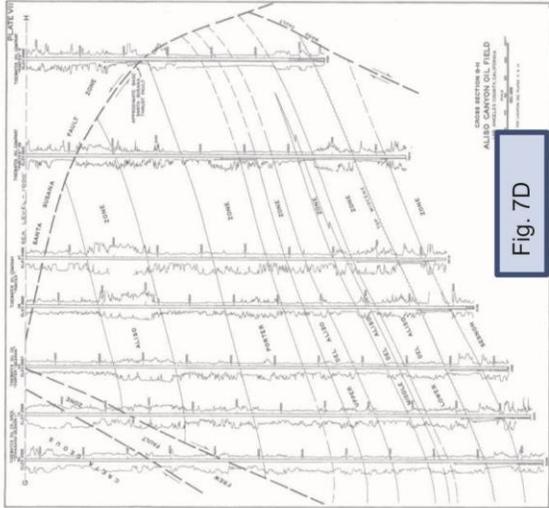
Fig. 7D

Aliso Canyon Field summary:

Discovery: In 1938 the Tide Water Associated Oil Company found oil and gas with the Porter #1 well (sec 27, 3N-16W). The Oat Mountain surface anticline was tested with Oligocene and Eocene age units as the intended targets. Serendipity played a big role as the Santa Susana thrust fault was not recognized at the time of testing and the Aliso Canyon field was discovered in the Pliocene age Porter zone below the fault (Kunitomi and Schroeder, 2001). IP for Porter zone was 700 BOPD of 22.1 degree oil and 200 MCFGD and one week later the well was producing 1,175 BOPD of 23.9 degree oil and 215 MCFGD (Ingram, 1959).

Trap: Faulted anticline in the footwall block of the Santa Susana thrust fault (Figure 5). Updip trap is provided by the Santa Susana, Roosa, and Ward faults (Figure 7C). All of the reservoirs are closed on the west by the Frew fault (Figures 6B & 7A), and all of the reservoirs are closed on the east by the east plunge of the subthrust anticline (Figures 5, 6B, & 7A) and additionally by pinchout of the Pliocene age sand reservoirs (Figure 7A).

Reservoirs: Pliocene age producing units are the Porter, Aliso, and Del Aliso zones; middle Miocene age producing unit is the Sesnon zone; and the Eocene age producing unit is the Frew zone. All of the producing units are marine sandstone beds and the elog character of the reservoir and sealing units are shown in the cross sections of Figures 7A-D. The average depth of the gas storage reservoir that is in the Sesnon and Frew zones is 8300 feet with an average thickness of 200 feet, average porosity of 23% and permeability of 85 MD, and original pressure of storage zone was 3600 psig. The Pliocene age reservoirs range in depth from 3900-6500 feet with a gross thickness of 2200 feet, average porosity of 25%, and an average porosity of 150 MD (Kunitomi and Schroeder, 2001),

Oil and gas: Pliocene age reservoirs produce oil in the lower 20 API degree and ~300 cubic feet of gas per barrel of oil. The deeper Sesnon and Frew zones had very large gas caps.

Volumes: 60.1 MMBO and 225 BCFG recovered, DOGGR (2009). The Sesnon and Frew zones originally had a significant gas cap of 100 BCF and 50 BCFG in solution (Kunitomi and Schroeder, 2001). As of 2009 the Sesnon and Frew zones have produced 28.3 MMBO and the three shallow Pliocene age zones 31.9 MMBO (DOGGR, 2009).

Key references: Additional geologic information on the Aliso Canyon gas storage field and earlier oil field operations, and the eastern Ventura basin adjacent to Aliso Canyon are in Hodges and Murray-Aaron (1943), Ingram (1959), Lant (1977), Yeats (2001), Yeats, et al. (1994), Kunitomi and Schroeder (2001), Tsutsumi and Yeats (2001).

Gas storage operations at the Aliso Canyon field (summarized from Kunitomi and Schroeder (2001): Aliso Canyon is the largest gas storage field in southern California and among the 10 largest in the United States. Aliso Canyon is owned and operated by Southern California Gas Company (SCGC). SCGC obtained the Sesnon and Frew zones for gas storage in 1972 and the Pliocene age zones in 1993. The field has a working inventory of 70 BCFG that can be delivered at rates approaching 2 BCFGD, 90 BCF cushion to maintain 1.2 BCFGD withdrawal with no impact on working inventory. Gas withdrawal rates average about 30 MMCFGD. Oil production from the storage zone averages 495 BOPD with water production averaging 771 BWPD. In addition to the gas storage operations SCGC produces oil from the shallower Pliocene age reservoirs (Aliso, Porter, and Del Aliso). Oil production averages 110 BOPD with 4000 BWPD. Presently the Pliocene sands are being water-flooded with 7 injectors and 4 disposal wells.

Petroleum system of the eastern Ventura basin: Oil in the eastern Ventura basin is probably sourced from the Monterey Formation (locally called Modelo; Figure 8A). Figures 8B and 8C show the geohistory of a deep part of the basin near the Castaic Junction field. This thermal modeling suggests that the top of the thick Modelo is just now beginning oil generation (Figures 8B, 8C, and 8D). In contrast, oil generation near the base of the Modelo began during Pico time (about 3 Ma) and accelerated during rapid deposition of the Saugus Formation. Lower Modelo strata may be generating gas today, accounting for the free gas pools that occur 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 Aliso canyon and other eastern Ventura fields probably changed markedly in the last 1 Ma due to crustal shortening and uplift. Miocene and Pliocene isopach maps (Yeats, et al., 1994) suggest that before shortening started oil generated in the lower Modelo Formation migrated southward and northeastward from an elongate east-west low

centered at the present location of Newhall-Potrero field. Figure 2, a present-day top Modelo structure map, implies that migration paths are now much more tortuous and shorter. Large amounts of oil are today migrating into the crests of the anticlines at Newhall-Potrero, Castaic Junction, and several other fields. Aliso Canyon oil may have been delivered along a variety of migration paths, and may have migrated before and/or after shortening began.

Directions: If time allows we will drive to the top of Oat Mountain that offers excellent views of the eastern Ventura basin, the San Fernando Valley, and the Santa Clarita Valley.

Oat Mountain and discussion of the eastern Ventura basin: Oat Mountain is along the crest of the Santa Susana Mountains which have uplifted and exposed rocks of the petroliferous eastern Ventura basin. 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 (Davis and Namson, 1994; Yeats, et al., 1994; Davis, et al., 1996). During Miocene and Pliocene time the eastern Ventura basin was a graben between the Oakridge fault system on the south and the San Gabriel fault and an unnamed large normal fault observed only in the subsurface on the east and northeast. Late Pliocene and Quaternary convergence caused the Santa Susana Mountains anticlinorium to grow and propagate northeast and ramp up the unnamed normal fault. The full geometry and extent of the Miocene and Pliocene age southern margin of the eastern Ventura basin remains unclear as it is masked by the hanging wall sheet of the Santa Susana thrust fault and the deeper north-dipping Roosa reverse fault.

From Oat Mountain are very good views to the south and north of the extent and geology of the Miocene to early Quaternary eastern Ventura basin. To the northeast deep erosion of Towsley and several other parallel canyons provide easily accessible transects through the basinal portions of a typical southern California coastal basin. Canyon wall exposures provide an excellent record of deep marine deposition during the late Miocene and Pliocene, basin shoaling beginning in the late Pliocene, and non-marine deposition during the Quaternary. Winterer and Durham (1962) in their pioneering work on deep-water deposition provide an excellent map, field descriptions, and paleo-environmental interpretation of this area.
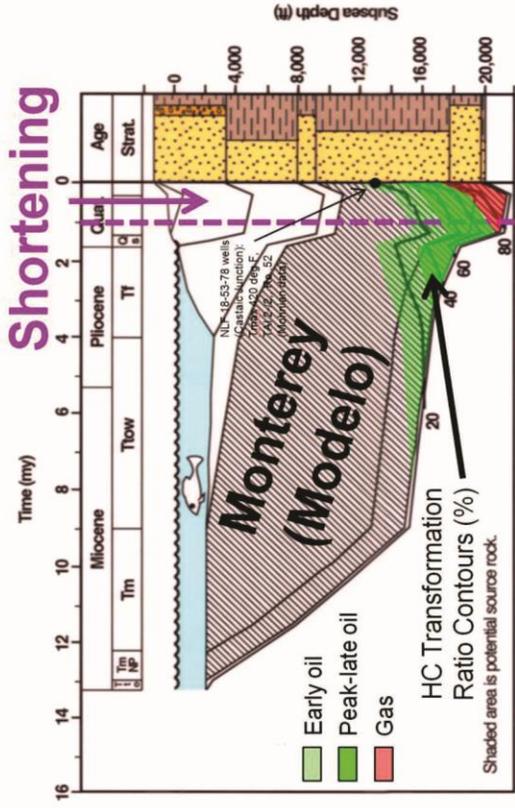
Figure 8B. Eastern Ventura kitchen burial history showing transformation ratio (%) in the Castaic field vicinity. Composite of Exxon NL&F #18, 53, and 78 wells. Heat flow = 1.1 HFU.
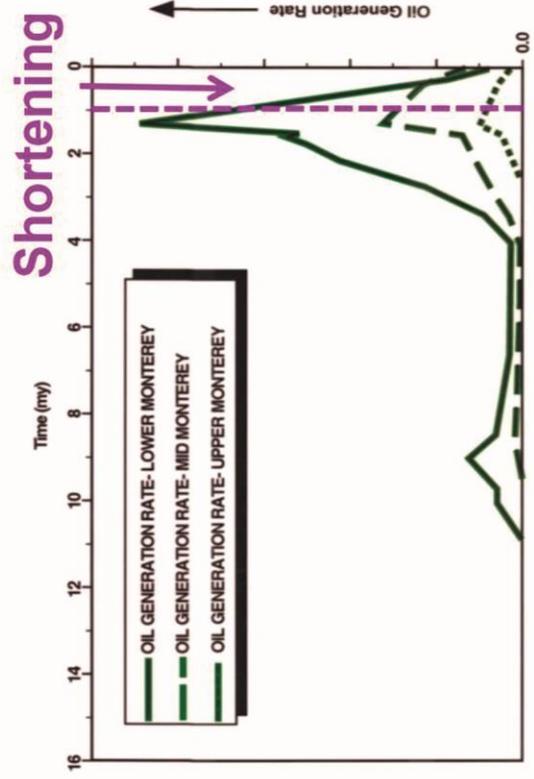
Figure 8D. Eastern Ventura kitchen Monterey oil generation rates versus time.
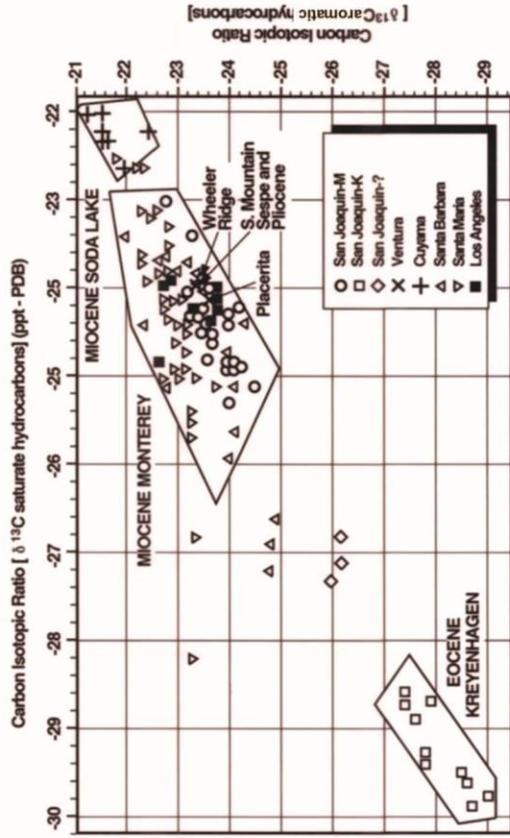
Figure 8A. California oil families showing Placerita, Wheeler Ridge, and South Mountains fields. Courtesy of Albert Holba, ARCO Exploration and Production Technology Company.
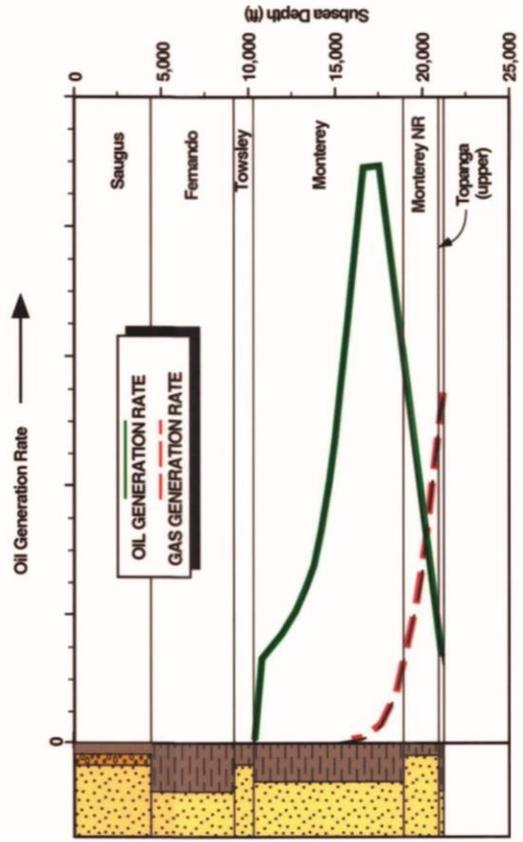
Figure 8C. Eastern Ventura kitchen hydrocarbon generation rates versus depth.

Directions from Stop #1 to Fillmore: Return to Hwy 118 via Aliso Canyon field road and Tampa Avenue. Go east on 118 Fwy until the 405 Fwy and go north over the Newhall Pass. Pass town of Valencia and take Hwy 126 west towards Ventura and Santa Paula. Pass through the town of Fillmore.

Regional cross section 8-8' (Namson and Davis, 1991) and
of the structure of central Ventura basin near Fillmore:

Regional cross section 8-8' (Figure 9A) shows Namson's interpretation of the deep structure of the central Ventura basin from the Oak Ridge-Montalvo anticlinal trend northward to the Sespe Creek synclinorium (cross section is labeled 7-7' in the 1991 report). The Santa Clara River valley is underlain by the east-west trending, deep 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 under the anticline. Surface and subsurface data show the anticlinal trend to be asymmetric with a moderate-dipping south limb and a steep to overturned north limb. A structure map, a kinematic model, and three cross sections across of the Oak Ridge-Montalvo anticlinal trend and southern portion of the deep Ventura basin are shown in Figures 10A-E (also shown in Davis, et al., 1996). The town of Fillmore is located just north of the cross section shown in Figure 10E. All three cross sections have structural styles in common which include the north-verging asymmetric anticlinal trend separated from the deep Ventura basin by the south-dipping Oak Ridge fault. The anticlinal trend is interpreted to be a fault-propagation fold associated with a south-dipping ramp on the South Mountain thrust. Cross section 8-8' (Figure 9A) shows the South Mountain thrust to be a back thrust off a splay of the San Cayetano thrust that crosses the deep basin and links deformation on the north side of the basin with deformation on the south side of the basin. The Oak Ridge fault is shown as a late Miocene and Pliocene age normal fault that has been cut, rotated, translated and reactivated by north-south directed convergence during the late Pliocene and Quaternary. In Figure 10E the South Mountain thrust is interpreted to propagate up the synclinal axis cutting and translating the Oak Ridge fault toward the surface. Slip on the South Mountain thrust is 2.6 km.

Across the Ventura basin, the Santa Ynez Mountains anticlinorium is composed of several folds and related thrust splays of the San Cayetano thrust (Figure 9A). One splay of the San Cayetano thrust (SCT 1) is interpreted to cause a south-verging fault-bend fold (Lion Mountain

anticline) that is associated with a ramp from a lower detachment at the top of the Monterey Formation to an upper detachment within the Pliocene Pico Formation. Approximately 3.6 km of slip is translated up the ramp and 2.6 km of slip is translated onto the upper detachment. Slip on the upper detachment cuts and offsets the Oak Ridge fault and finally the slip is transferred onto the South Mountain thrust. Two fault splays (SCT 2 and the Pagenkopp fault) cut to the surface and have associated hanging wall deformation. The SCT 2 has the most significant stratigraphic throw because it juxtaposes Eocene strata in the hanging wall of the SCT 2, which is otherwise a cross cutting section that extends down into the Franciscan Assemblage. The cross cutting hanging wall section is related to two ramp sections on the San Cayetano thrust system which root in a basal detachment at about 11 km depth. Slip on this large ramp is 29.9 km. The Pagenkopp fault is interpreted to be a minor splay of the SCT 2. The Pliocene and Quaternary section are overturned in the hanging wall. The minimum slip on the Pagenkopp fault splay is 1.5 km.

The present-day cross section 8-8' is 32.5 km in length and the restored cross section is 67.6 km which yields a convergence of 35.1 km (Figures 9A & B). The convergence rate between the Oak Ridge anticline and the Pine Mountain fault is 8.8-17.6 mm/yr, assuming convergent deformation started between 2.0-4.0 Ma.

Figure 9A. Regional cross section 8-8' from Sespe Creek synclinorium to the Oak Ridge-Montalvo anticlinal trend. Figure 9B. Line-length restoration that removes late Pliocene and Quaternary convergence (Namson, 1987). The south vergent Santa Susana thrust fault system terminates before reaching the portion of the basin shown in cross section 8-8'. At cross section 8-8' the shallow portion of the southern margin of the deep basin is folded by north vergent deformation. The structural shelf along the southern margin of the deep basin remains between the two areas (just above the label 2.6 km slip in Figure 9A) and is equivalent to the Aliso Canyon field area in the footwall of the Santa Susana thrust fault.
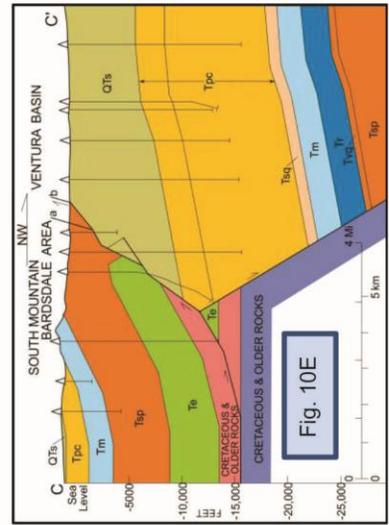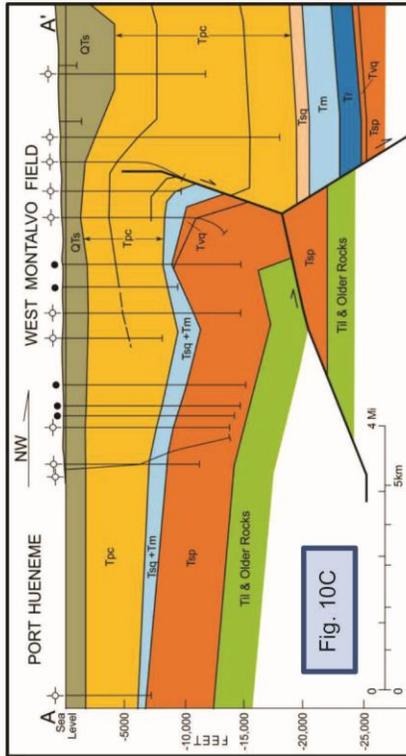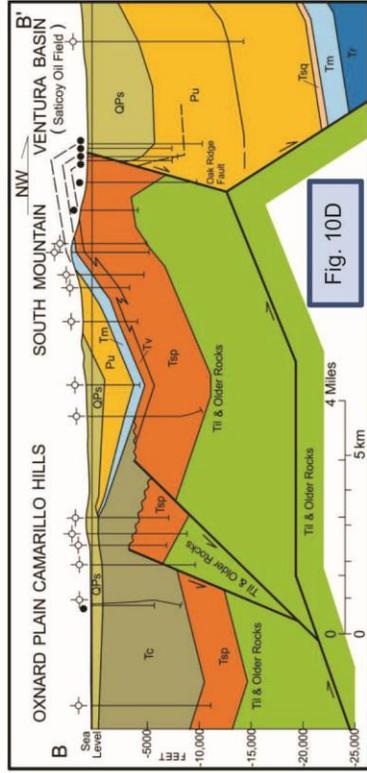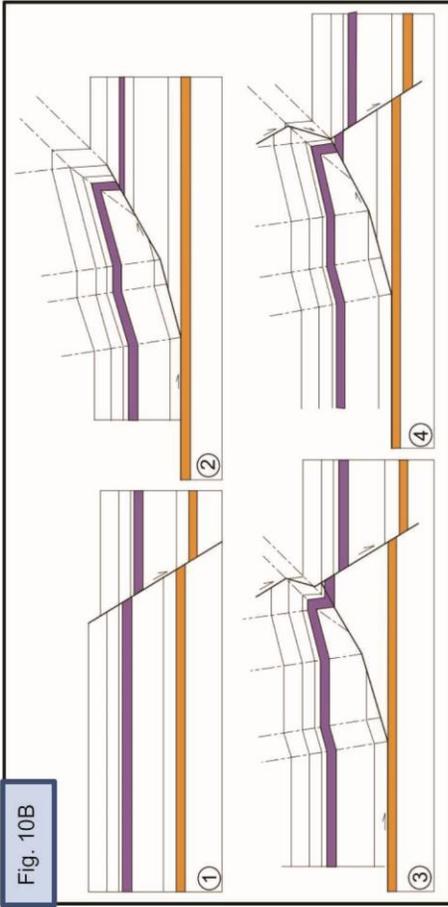
Figure 10A. Structure contour and oil field map of the western Ventura Basin (modified from Hindle et al., 1991 and DOGGR, 1992).
Figure 10B. Schematic models showing the interaction between a normal fault and a fault-propagation fold. 1. Normal fault with initial dip of 60°. 2. Fault-propagation fold with gentle back limb and steeply-dipping front limb. 3. Normal fault becomes deformed and rotated as a passive marker horizon on the front limb of the fault-propagation fold. 4. Increased thrust slip results in more structural relief on the anticline and a longer rotated normal fault along the front timb.
Figure 10C. Cross section A-A' through the Oak Ridge-Montalvo trend near the Montalvo oil field.
Figure 10D. Cross section B-B' through the Oak Ridge-Montalvo trend near the South Mountain oil filed.
Figure 10E. Cross section C-C' through the Oak Ridge-Montalvo trend near the Bardsdale area.

Directions from Fillmore to Santa Paula and lunch stop: *From Fillmore continue west on 126 towards Santa Paula. Exit the freeway at 10th Street in Santa Paula. We will stop for lunch in or near Santa Paula.*

Discussion of the Oak Ridge fault and South Mountain oil field as we near Santa Paula (this trip does not stop at South Mountain oil field; the oil field and structure are described in detail in Davis, et al, 1996): To the south of Hwy 126 and across the Santa Clara River Valley is the South Mountain oil field. The oil field is located below the ridge line, along the Oak Ridge-Montalvo anticlinal trend, and oil is trapped in a local culmination called the South Mountain anticline. Oil is produced from sandstone beds of the nonmarine Sespe Formation. Northwest of the South Mountain oil field and at the base of the ridge is the Saticoy oil field that produces oil from sandstone beds of the Pico Formation that are trapped below the south-dipping Oak Ridge fault. The Oak Ridge-Montalvo anticlinal trend appears to be mostly 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.

Directions from Santa Paula to Stop #2: *Following lunch continue north on 10th Street towards Ojai (10th Street is now Hwy 150). Pass Thomas Aquinas College, and access road to the Silverthread area of the Ojai oil field is on the right and a short distance past entrance to the college.*

Stop #2, Silverthread Area of the Ojai oil field

Geologic summary: Stop # 2 is located just east of upper Ojai Valley where we will view and discuss the complex structural setting of the Silverthread area of the Ojai Valley oil field (Figures 11 & 12A). We will walk a short distance to view the San Cayetano thrust fault which is one of the most important faults of the western Transverse Ranges (Dibblee, 1982). West of Stop #2 the San Cayetano fault does not reach the surface, but regionally, this "blind thrust" portion of the fault is very important as it is the cause of the uplift of the Santa Ynez-Topatopa Mountains and folding along the north side of the Santa Barbara Channel from Ojai west to Point Conception.

Figure 13 is a structure contour map of the San Cayetano thrust from Timber Canyon west to the Silverthread area and Stop #2. The map, constrained by well data and the surface mapping, show a fairly planar fault surface that dips northward about 40-50 degrees. At the surface of the Stop #2 location the Dibblee map (Figure 11) shows the northern trace of the San Cayetano thrust fault has emplaced the Eocene age Coldwater Formation over the Miocene age Monterey Formation, and the southern trace of the fault has emplaced the Monterey Formation over Pliocene-age Pico Formation (shown as Saugus Formation by Mitchell, 1968). To the south of Stop #2 the south-dipping Sisar fault emplaces the Monterey Formation over the Pico formation. Stop #2 is located just east of the cross section 7-7' line (Figure 12A, and figure labeled "A" on guidebook cover). Integration of the surface mapping and oil well data reveal a "triangle-zone" structure (see figure labeled "B" on field trip guidebook cover).

The subsurface interpretation shown in regional cross section 7-7' near Stop #2 has the San Cayetano thrust fault separated into two major splays (Figure 12A): 1) an upper splay labeled SCT2 that is the splay that occurs at the surface at Stop #2 and emplaces Eocene age rocks (Te) over the Miocene and Pliocene age rocks (Pu, Tsq, Tm), and the deeper splay labeled SCT1 is interpreted to form the large fault-bend fold anticline with the front limb observed along the north side of the Ventura basin. The Big Canyon fault is interpreted to be an older normal fault that is cut, translated, and folded as it moved from the lower part of the SCT1 fault ramp onto the upper detachment. The Big Canyon fault trace reaches the surface west of Stop #2 Figure 11) but the fault is defined mostly from subsurface data, and the fault 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 SCT1. The undeformed original geometry of the Big Canyon fault is shown in the cross section restoration (Figure 12B). Understanding the Big Canyon fault is of importance as it is an important oil-trapping structure at the Ojai oil field.

Figure 11. Surface geologic map of the Santa Paula Peak 7.5' quadrangles by T.W.Dibblee Jr. Paper Dibblee maps are available for purchase from the Santa Barbara Museum of Natural History: www.sbnature.org/dibblee/. Regional cross section 7-7' is shown in Figure 12.

Regional cross section 7-7' (constructed by Namson and first shown in Namson and Davis, 1991):

Cross section 7-7' begins offshore at the western end of the Santa Monica Mountains and crosses South Mountain, Topatopa Mountains, Pine Mountain, Frazier Mountain and ends at the San Andreas fault (Figure 12A). In the Namson and Davis 1991 report cross section is labeled 6-6'.

The first structure shown on the south end of cross section 7-7' is the Santa Monica Mountains anticlinorium. The geometry of the anticlinorium is constrained by surface geology of the Santa Monica Mountains and some subsurface drilling. The fold structure is asymmetric with a steep south limb that is only partially onshore and extends into the offshore. The crest of the fold occurs on the south part of the Santa Monica Mountains and the north limb is moderately dipping. The Santa Monica Mountains anticlinorium is interpreted to be a fault-propagation fold caused by the Elysian Park thrust which ramps up from a basal detachment at 15 km depth and terminates in an offshore synclinal axis at about 9 km depth. The slip on the Elysian Park thrust is 11.3 km.

The fold is cut by a series of Miocene age normal faults that controlled thick accumulations of volcanic rocks. The Malibu Coast fault is projected offshore into the cross section, where it cuts the south limb of the anticlinorium. The fault juxtaposes contrasting stratigraphic sections: south of the fault the Miocene strata lie unconformably on metamorphic basement rock and north of the fault is the thicker Miocene section as well as lower Tertiary and Cretaceous rocks which sit unconformably on metamorphic or Franciscan basement. These relationships suggest to us that the Malibu Coast fault is a Miocene and older normal fault that was down to the north. It may have been reactivated as a reverse fault during the late Cenozoic formation of the Santa Monica Mountains anticlinorium.

The next structures to the north are a pair of anticlines that include the Oak Ridge-Montalvo anticlinal trend and an unnamed anticline to the south. The Oak Ridge-Montalvo anticlinal trend is defined by surface geology and subsurface drilling and is asymmetric with a gently dipping south limb and steeply dipping north limb. The north limb is cut by the steeply south dipping Oak Ridge fault. The unnamed anticline is primarily defined by subsurface data. The

fold has moderately dipping limbs and the crest is broken up by several normal faults. The normal faults are predominantly down to the south and control accumulations of volcanic rock.

The interpretation shows the two anticlines to be related to ramps on the South Mountain thrust which is a back thrust off the lower splay in San Cayetano thrust fault (SCT 1). The unnamed anticline is interpreted to be a fault-bend fold associated with a ramp that steps up from a lower detachment at 8 km to an upper detachment at 6 km. The Oak Ridge-Montalvo anticlinal trend is interpreted to be a fault-propagation fold associated with the second ramp on the South Mountain thrust. The Oak Ridge fault is shown as a rotated normal fault that was active during late Miocene and Pliocene time and originally dipped north. The South Mountain thrust translated slip up the rotated segment of the normal fault reactivating the fault as a high angle reverse fault. The slip translated up the ramp for the unnamed fold is 4.0 km and slip translated up the ramp below the Oak Ridge-Montalvo anticlinal trend is 3.9 km.

On regional cross section 7-7' (Figure 12A) the Santa Ynez Mountains anticlinorium lies north of the deep central portion of the Ventura basin. The anticlinorium includes the structures underlying Sulphur Mountain and the Topatopa Range. In cross section 7-7' Sulphur Mountain lies above the Sisar thrust fault, and the thrust is a north-verging thrust with an asymmetric anticline in the hanging wall. The Sisar fault is interpreted to be a back-thrust off 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 Sisar thrust is shown to ramp up from the base of the Rincon shale forming a small fold in the hanging wall. At the surface the Sisar thrust is truncated by the upper splay of the San Cayetano thrust system (Figure 11; SCT 2 in Figure 12A). The Santa Ynez Mountains anticlinorium is composed of several stacked fold and complicated faults that are observed at the surface and encountered in subsurface drilling. The deepest structure is a fault-bend fold that is in the footwalls of the Sisar thrust and upper San Cayetano thrust splay (SCT 2). The fault-bend fold is associated with a ramp in the deeper San Cayetano thrust splay (SCT 1). The ramp connects a lower detachment near the base of the Eocene strata to an upper detachment at the base of the Rincon shale. The SCT 1 cuts and translates the Big Canyon fault and the Oak Ridge fault which are older normal faults.
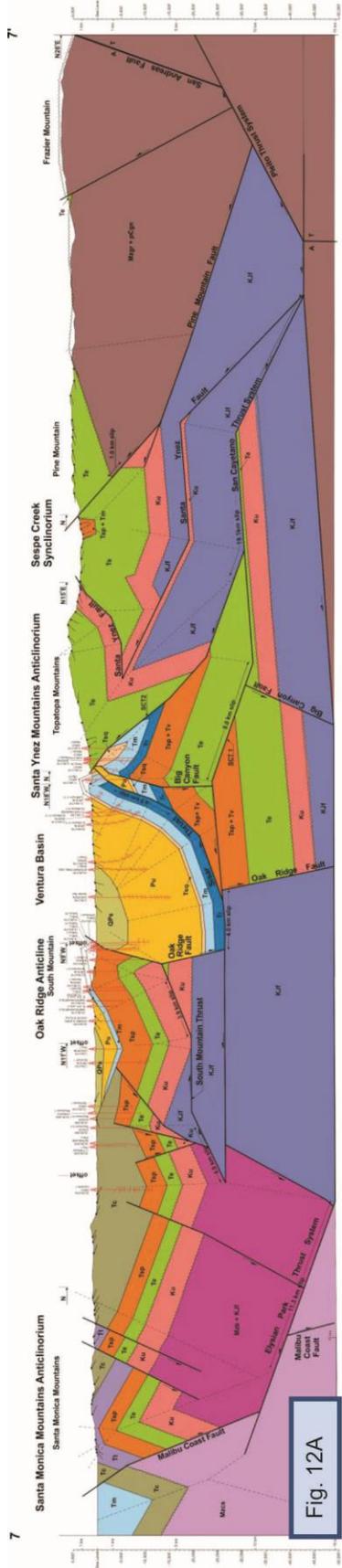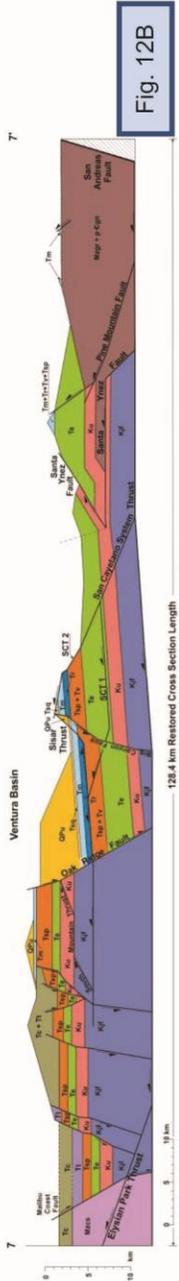
Figure 12A. Regional cross section 7-7' (Namson and Davis, 1991) from the Santa Monica mountains to the San Andreas fault.

Figure 12B. 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.

Figure 12C. Huftile and Yeats (1995) cross section C-C'. Yeats and Huftile (1989) were highly critical of Namson and Davis' 1989b interpretation and approach, but remarkably and seven years later, Huftile and Yeats published a similar interpretation.

Geologic unit abbreviations for cross section: pCgn= Precambrian and possibly younger high temperature metamorphic rocks; Mzgr= Mesozoic age plutonic rocks, Mzcs= Cataline Schist; KJf= 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.

The Big Canyon fault is translated and folded as it moved from the lower part of the ramp onto the upper detachment whereas the Oak Ridge fault is only translated along the upper detachment. Approximately 8.0 km of slip on the upper detachment of the SCT 1 is divided and consumed equally between two back thrusts, the South Mountain thrust and Sisar thrust.

The surface geology of the Santa Ynez Mountains anticlinorium is dominated by a thick Eocene section that is deformed into an overturned fold in the hanging wall of the SCT 2. This overturned fold is interpreted to be a fault-propagation fold that has been cut and translated on the San Cayetano thrust system and breaks through to the surface. The original ramp steps up from a basal detachment within the Franciscan basement at about 13 km to the top of the Eocene. The upper part of the ramp has been cut and translated by the SCT 1 and continued to slip on the SCT 2 fault that ruptured to the surface up the frontal synclinal axis of the fault-propagation fold. Approximately 19.1 km of slip has been translated up the ramp on the San Cayetano thrust system.

In Namson's 1987 interpretation the Santa Ynez fault is shown to be a late Eocene age fault associated with the Ynezian orogeny (see "D" figure on field trip guidebook cover). This interpretation shows it as a north-verging back thrust from a south-verging fold and thrust structure. Subsequent late Pliocene and Quaternary folding in the hanging wall of the San Cayetano thrust system further deformed the Santa Ynez fault geometry.

Along cross section 7-7' and north of the Santa Ynez anticlinorium and Sespe Creek synclinorium are Pine Mountain and Frazier Mountain. Late Cenozoic uplift and folding of Pine Mountain and Frazier Mountain are interpreted to be related to the Pine Mountain fault. The Pine Mountain fault juxtaposes the Salinian and Franciscan basement terranes. This juxtaposition must have occurred prior to Eocene time because the Eocene units occur unconformably on both blocks. Late Cenozoic deformation of the Pine Mountain fault ruptured though the steep north limb of the syncline to the surface. There is approximately 2.4 km of shortening associated with the blind thrust and fault propagation fold and about 1.0 km on the Pine Mountain fault splay that rupture to the surface. The Pine Mountain fault is interpreted to root into a north-verging ramp on the Pleito thrust system which causes the uplift and folding of the San Emigdio Mountains north of the San Andreas fault and offset of the San Andreas in

the deep crust. The relationships between thrusts of the western Transverse Ranges and San Andreas fault are discussed in Namson and Davis (1988b and 1989).

The present-day length of regional cross section 7-7' is 95.2 km and the restored cross section length is 128.4 km which yields 33.2 km of convergence (Figures 12A &B). The convergence rate from the western Santa Monica Mountains to the San Andreas fault is 8.3-16.6 mm/yr., assuming convergent deformation started between 2.0-4.0 Ma.

San Cayetano Thrust Fault (taken from Hester, 1977):

Timber Canyon Lobe: The Timber Canyon Lobe between Sespe and Santa Paula Creeks consists of a massive series of upper and lower Eocene sediments thrust over upper Pliocene Pico Formation (see sections G thru O-this guidebook shows section M-M' and O-O')

Timber Canyon itself is one of the more impressive topographic anomalies existing along the San Cayetano thrust zone. The canyon is a steep expanding flood plain ripped off the south side of Santa Paula Peak and carved through relatively soft Pliocene sediments in a straight fall line.

Along much of its outcrop in this lobe, the thrust scarp is usually associated with a thin wedge of the Miocene Monterey shale about 20 ft. thick. This wedge has been caught up along with the movement and is often encountered in wells drilled through the fault. The shale has originally served as a lubricant between moving blocks, and now should serve as a positive seal to any reservoir trapped below. Along the Timber Canyon over-thrust area three blocks containing a similar sequence of overturned sediments are described on the accompanying sections (G thru O) labeled Blocks A, B, C and contain the same Pliocene Pico and Repetto sand and shale present in Timber Canyon oil field.

Block A was originally overridden to the north by Block B along a now overturned thrust, Ott fault. Block B in turn has the same relation with Block C along the Anlauf thrust which was also overturned. The San Cayetano thrust overrides Block C from the north.

Block A has several outcropping tar sands equivalent to the producing sands of the field; Block B is the producing block at Timber Canyon; Block C remains untested except for the Loel-

Maxwell #1 and #2 wells to the east. Positioning of these blocks by original thrusting from the south immediately preceded the San Cayetano overthrusting from the north which created the overturn of the rocks and fault planes.

Silverthread-Sisar Lobe: The most westerly lobe of the San Cayetano thrust lies between Santa Paula Creek and Lower Ojai Valley. In general Eocene sediments form the north overriding block in this lobe. On the east side of the Silverthread area near the Santa Paula Creek reentrant the south block consists of overturned Pliocene Pico Formation. As the thrust continues to the west Eocene is over Miocene Monterey Formation. Pico sediments are separated from the Monterey by the Big Canyon fault which curves northward and disappears beneath the San Cayetano thrust. Farther west the north block overrides lower Miocene Vaqueros sediments. Although both blocks are overturned the magnitude of the displacement diminishes progressively to the west until the thrust eventually dissipates under Ojai Valley.

Occasional maroon shale outcrops along the fault front at Silverthread have been called Sespe, but at its type locality the uppermost Coldwater beds contain a considerable thickness of Sespe-like colored shales below the first type Coldwater sand. The outcrops at Silverthread could be either.

The Lion Mountain-Sisar area south of the San Cayetano surface trace is the normal north flank of the Lion Mountain anticline which plunges easterly toward Silverthread. The north flank is cut off by the San Cayetano thrust and the south flank intercepts the south-dipping Big Canyon fault. (see map Ojai-Silverthread area).

The extensive Matilija overturn north of Ojai Valley and west of the last visible trace of the San Cayetano thrust matches the tectonic pattern of the complete thrust front-but specific ties are obscure.
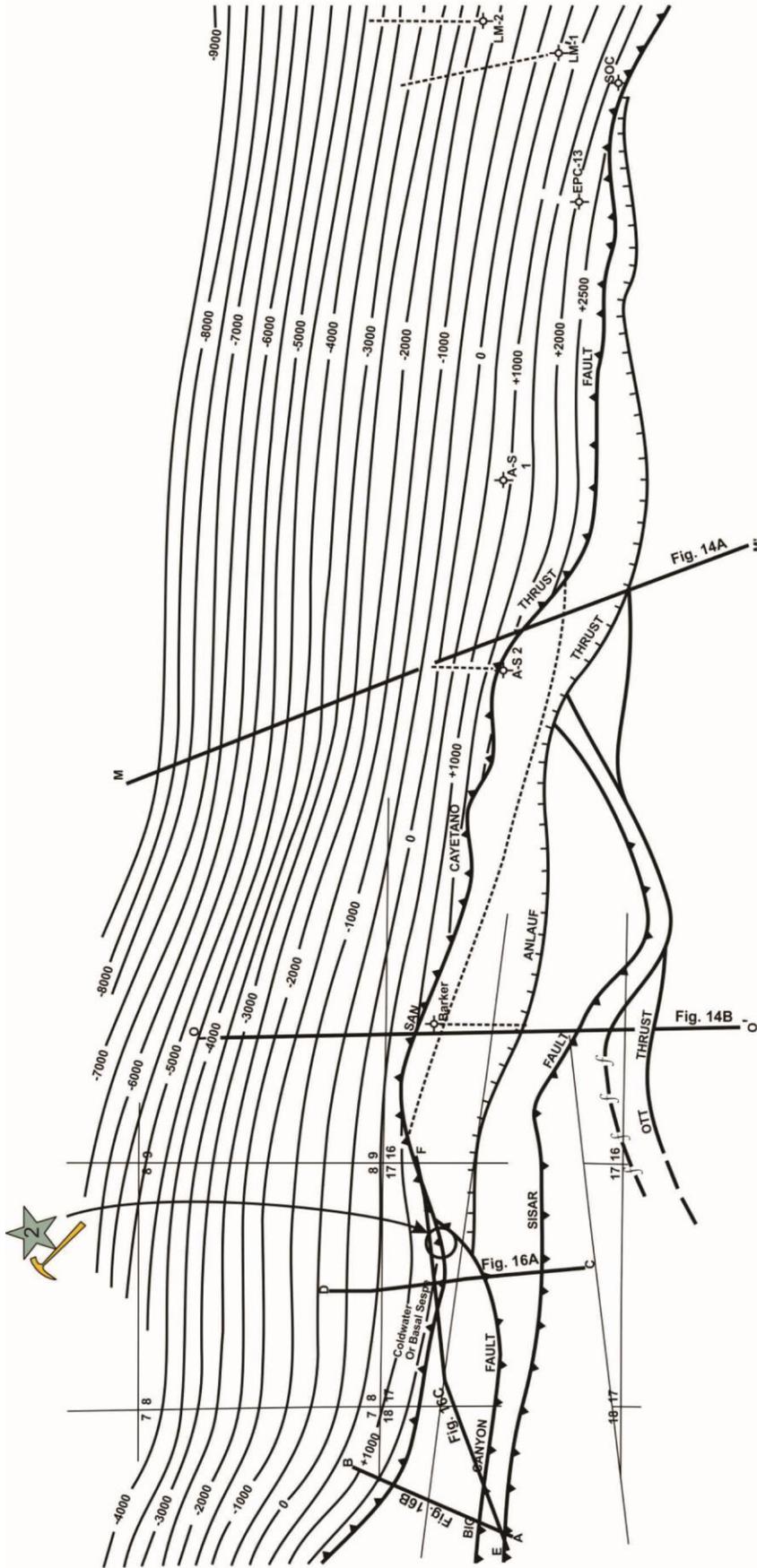
Figure 13. Structure map of the San Cayetano thrust fault (modified from R.L. Hester and J.N. Truex, 1977). Cross section lines A-B, C-D, and E-F are from Mitchell (1969) and cross section lines O-O' and M-M' are from R.L. Hester (1977). The following description is abbreviated from Hester (1977): The San Cayetano is a major fault extending across the mountain front north of the Santa Clara trough. It can be observed in outcrops as an east-west trending topographic break stretching along the 25 miles between Piru Creek and Ojai Valley. The terminals of the fault trace lose their identity under alluvium. The San Cayetano thrust probably intersects the Holser fault on the east as it curves northward following Piru Creek. On the west it either splinters and dies out beneath the lower Ojai Valley or intersects the Lion Mountain fault. It also has an interesting affinity with the Red Mountain thrust to the west but does not appear to be connected. The San Cayetano thrust is extensive, its plane dips northward at an average of 40-45° and has been cut by exploratory wells at depths approaching 10,000 ft., four and a half miles north of the surface trace (see fault contour map). The nature of the outcrop pattern conveniently separated the surface trace into four distinct segments: The Modelo lobe, the Sespe meander reentrant, the Timber Canyon lobe and the Silverthread-Sisar lobe. Although the fault trace reentrants at major stream crossings, Piru, Sespe and Santa Paula Creeks, are partly in response to topography and the dip of the fault plane, each of these lobes also involves varying rock types and ages on opposing sides. The major reentrants at Sespe and Piru are probably more the result of tectonic pressure. The fault trace can be recognized not only as a definitive topographic break but also as an abrupt change in vegetation. The lower block sediments are always younger than the overriding rocks and are often crushed leaving a grassy zone quite obvious in the field especially during springtime.
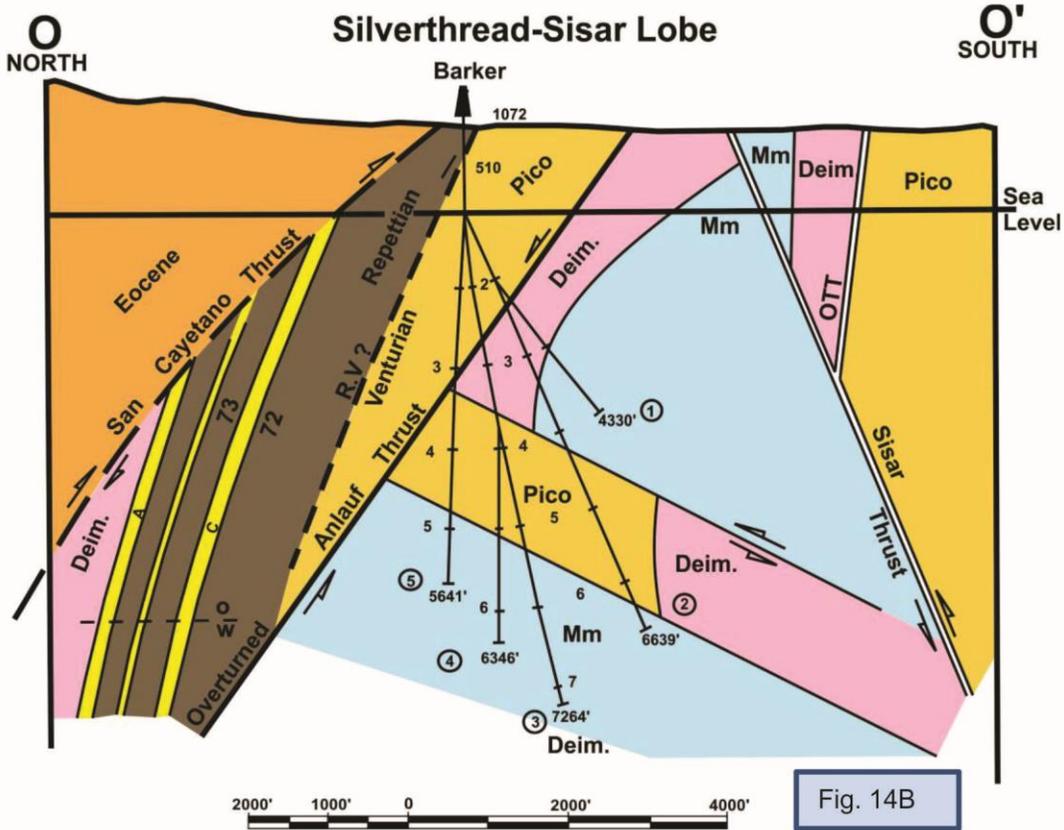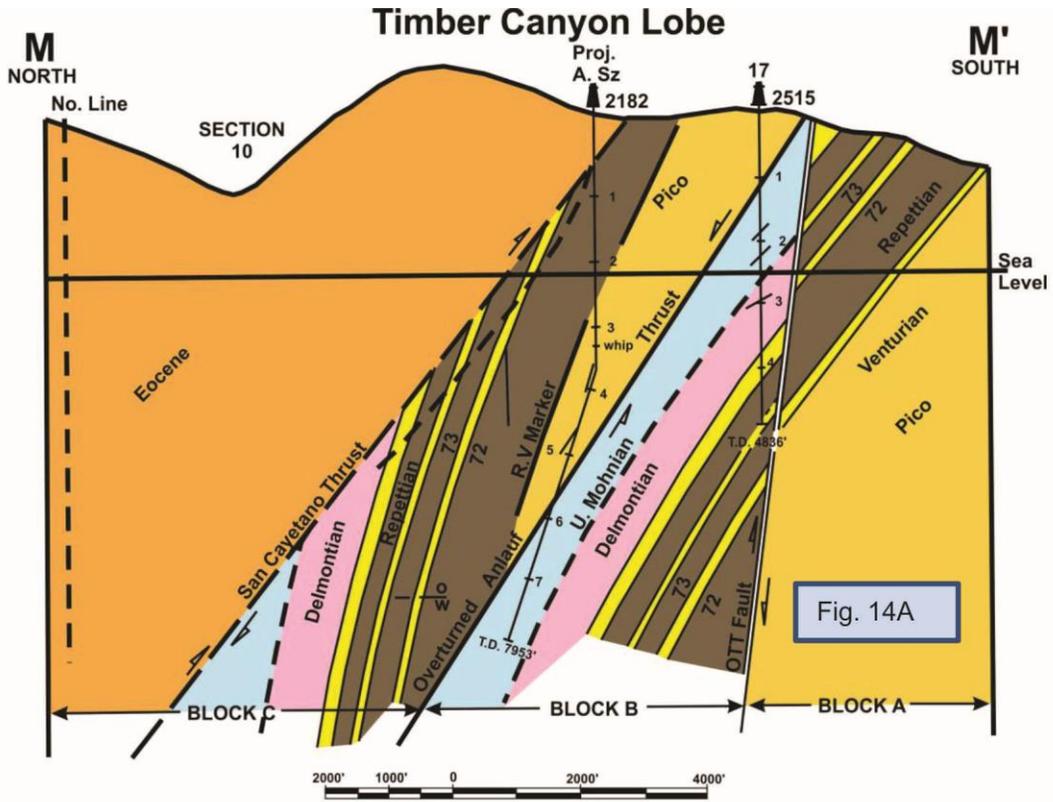
Figure 14. R.L. Hester cross sections of the Timber Canyon and Silverthread-Sisar lobes of the San Cayetano thrust fault (1977). See text for Hester's descriptions of the thrust fault, complex subthrust structural geometry and evolution, and oil traps.

Silverthread area field, Ojai oil field (summarized from Mitchell, 1968; and DOGGR, 1992): The Silverthread Area is the easternmost oil producing area within the Ojai oil field. Much of the oil production from the Ojai Valley oil field is from the footwalls of the Sisar and San Cayetano thrust fault 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.

Discovery and history: 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. The Philadelphia California Petroleum Company Ojai #6 well, drilled in 1866, IP'd at 15-20 barrels of "tar" per day, a 1876 report indicated the well was at 30 BOPD, and in 1884 was still producing. During the period from 1885 to 1898 Union Oil Company drilled eight additional wells in NE4 of section 18 and NW4 of section 17, several of which were still producing by the 1960s. By 1913 Capital Crude Oil Company, Bard Oil, and Asphalt Company were producing from forty-four wells in the N2 of sections 17 and 18. Pan American Petroleum Company took over Bard's and Asphalt's assets in 1917 and drilled one more well and Richfield Oil Company (later ARCO) took over the assets in 1937. In 1951 and 1952 Richfield began to explore to the north and south of the then known limits of the field. The Richfield Hillside #1 (later the Volunteer Petroleum Company Hillside #3) located in section 8 drilled to 9,955 feet and found significant oil shows in the lower Mohnian sand units below 6,100 feet; however after testing the well was deemed noncommercial. To the south the Richfield Ojai #67, located in section 17 drilled to 7,492 feet and found significant oil shows in the lower Mohnian and Luisian age sand units below the Big Canyon fault; however, after two redrills the well was deemed noncommercial. From 1920 to 1968 only five wells were completed in the Silverthread area including the H.A. Williams Hamp Fee #32 in section 17 drilled in 1968. 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. Increased drilling in the 1970's through 2002 increased production to 614.3 BOPD and 1,809.7 MCFD (DOGGR, 2002) and in 2009 production was 413 BOPD (DOGGR, 2009).

Trap: The Silverthread area has oil trapped within a "triangle zone" between the San

Cayetano and Sisar faults (Figure 16A). The Big Canyon fault provides an up-dip seal to both Saugus and Monterey Formation reservoirs that are dipping northward within the footwall block of the San Cayetano fault (note that Dibblee has mapped strata as Pico rather than Saugus, Figure 11). In cross section 7-7' (Figure 12A) the Big Canyon fault is interpreted as a pre-thrusting normal fault and presents the possibility that oil was trapped here before the emplacement of the Sisar and San Cayetano thrust faults. The basal Saugus unconformity developed across steeper dipping Monterey Formation does not play a significant trapping role at Silverthread, but just to the west and along strike the unconformity traps oil in the Sisar Creek area.

Reservoirs: Sandstone of the Saugus Formation, the Big Canyon fault zone, and deeper Monterey Formation production (lower Mohnian sand and fractured shale). The deeper sand is reported to have a porosity of 30% (DOGGR, 1992). 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. Productive intervals are sands within the Saugus Formation, the Big Canyon fault zone, and sands and fractures within the Monterey Formation.

Oil and gas: 22 API degree oil is produced from the undifferentiated Saugus and Monterey Formations while deeper reservoirs solely in the Monterey Formation produce 19-36 API degree oil (DOGGR, 1992).

Volumes: Cumulative production as of 2009 is 20.0 MMBO and 39.3 BCFG with the majority of production from intervals in the Monterey Formation (DOGGR, 2009).

Key references: Mitchell (1968), DOGGR (2002, 2009).
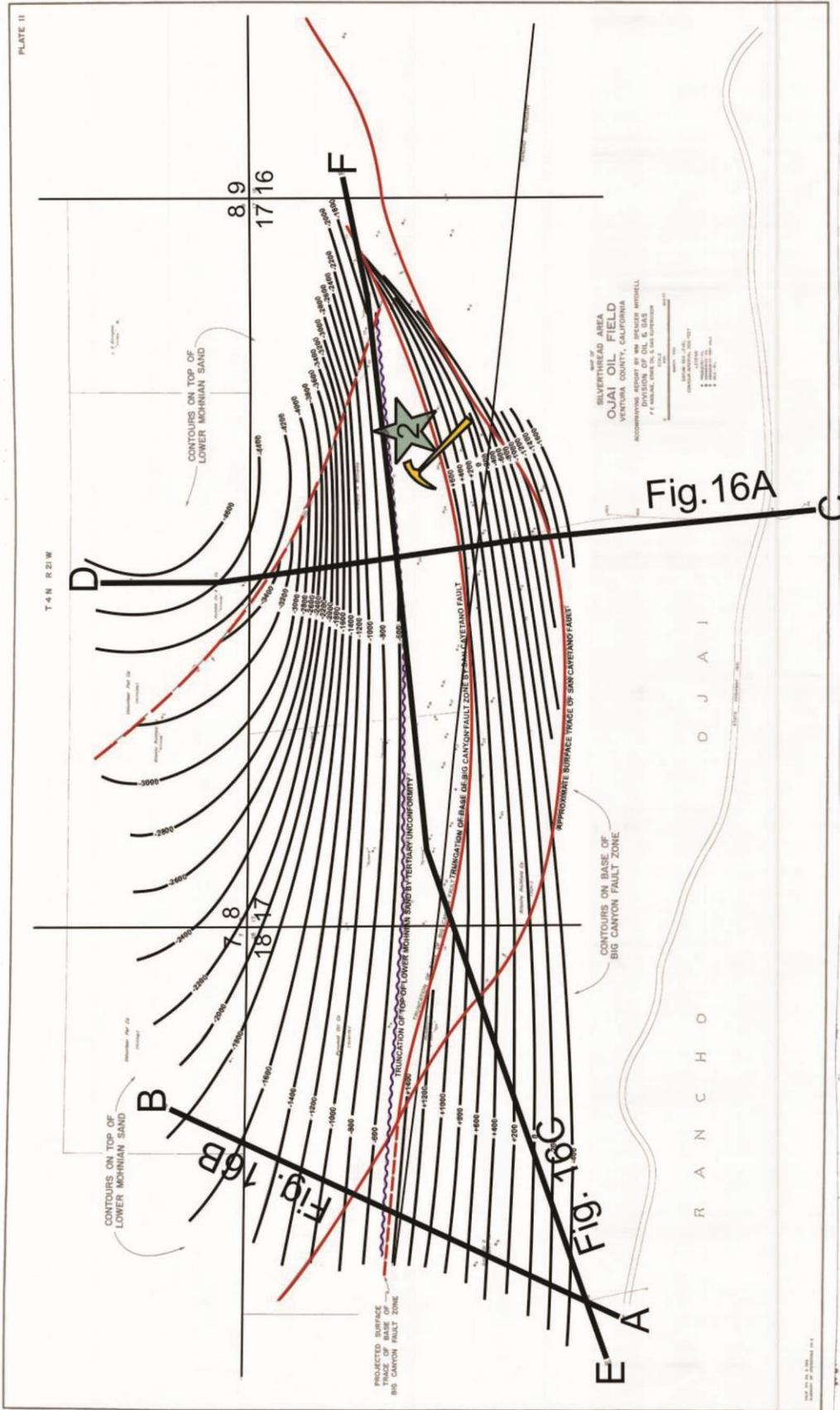
Figure 15. Structure map of the Silverthread area, Ojai oil field, from Mitchell (1968). Map shows field trip Stop #2 that is on the hanging wall block of the San Cayetano thrust fault, and the complex nature of the oil field that is in the footwall block of the San Cayetano thrust fault. Contours on north half of map are on top of lower Mohnian sand (within Monterey Formation), and contours on south side of map are on the base of Big Canyon fault zone. The Big Canyon fault is an important up dip trapping structure for both the Saugus and Monterey Formation reservoirs. Namson's cross section 7-7' (Figure 12A) shows the Big Canyon fault as a normal fault that is dipping steeply to the south and cut be the younger San Cayetano thrust fault.
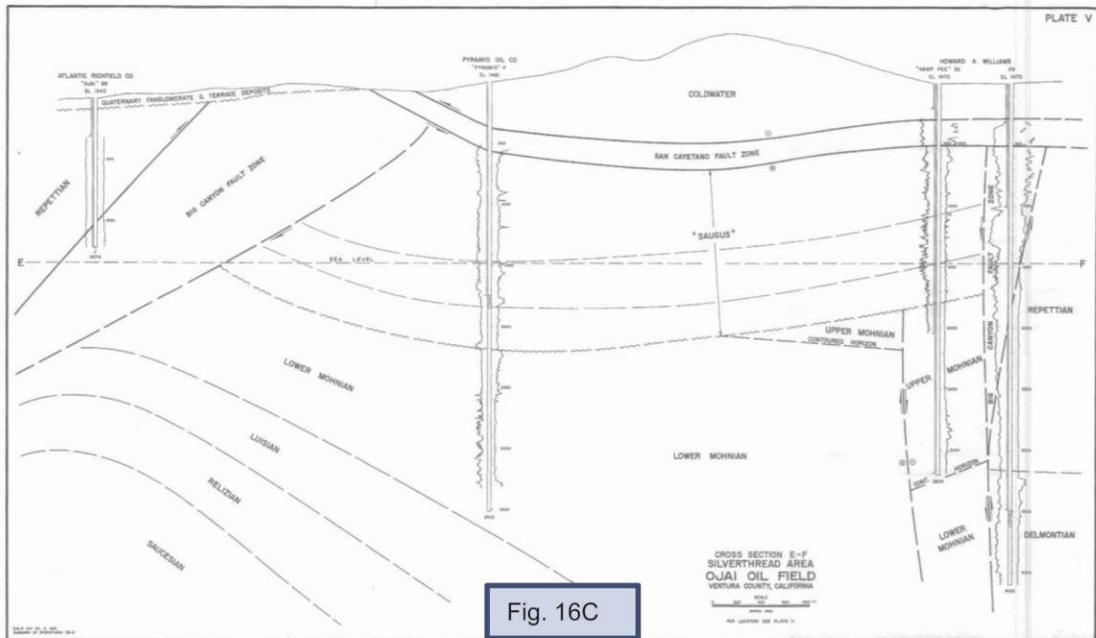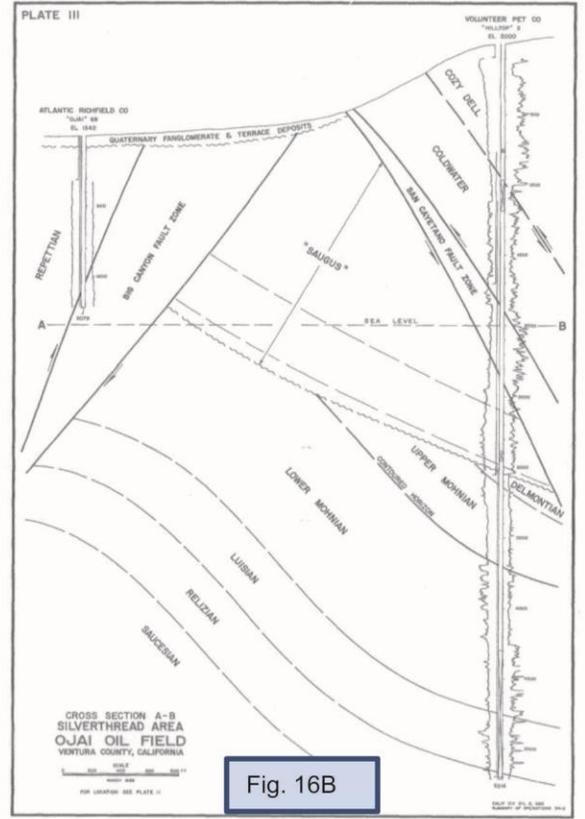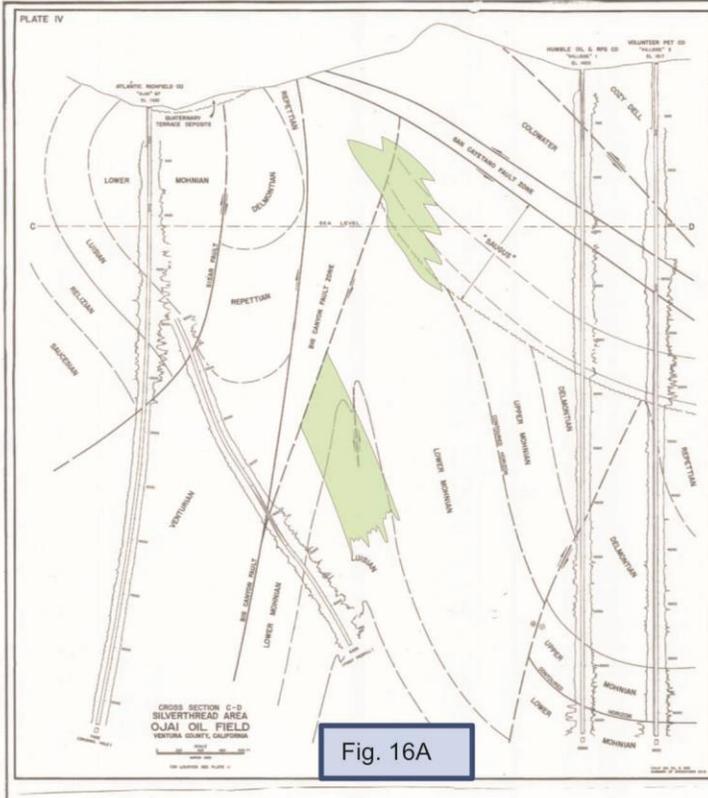
Figures 16A-C. Cross sections of the Silverthread area, Ojai oil field (Mitchell, 1968). Sections show the complex nature of the oil field in the footwall block of the San Cayetano thrust fault. Note up-dip and lateral trapping provided by the Big Canyon fault. Only Figure 16A shows the oil zones and are from DOGGR (1992).

Petroleum system of the central Ventura basin: 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 (Figure 8A) and at South Mountain oil field the Monterey Formation is immature (Figure 17A). 2) South Mountain oil field is bounded on the north by a deep central basin (Figure 10). 3) The deep central Ventura basin is generating oil today at great depths (6-7 km; Figures 17A & B) in a rapidly subsiding 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 both suggest that the Monterey Formation is not mature enough to generate gas (Figure 18A). This is consistent with the lack of free gas at South Mountain and the other oil fields in the central Ventura basin.

Figure 18B shows the sizes of oil fields in the Ventura basin. Most of the oil is in the west, with modest 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. Another factor is the predominant south dip of the central Ventura basin (Figures 9, 10, & 12). 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 (Figure 20). Finally, source rock data (Kaplan, 2000) and the paucity of siliceous strata suggest that source facies in the eastern Ventura basin may be thin and lean.
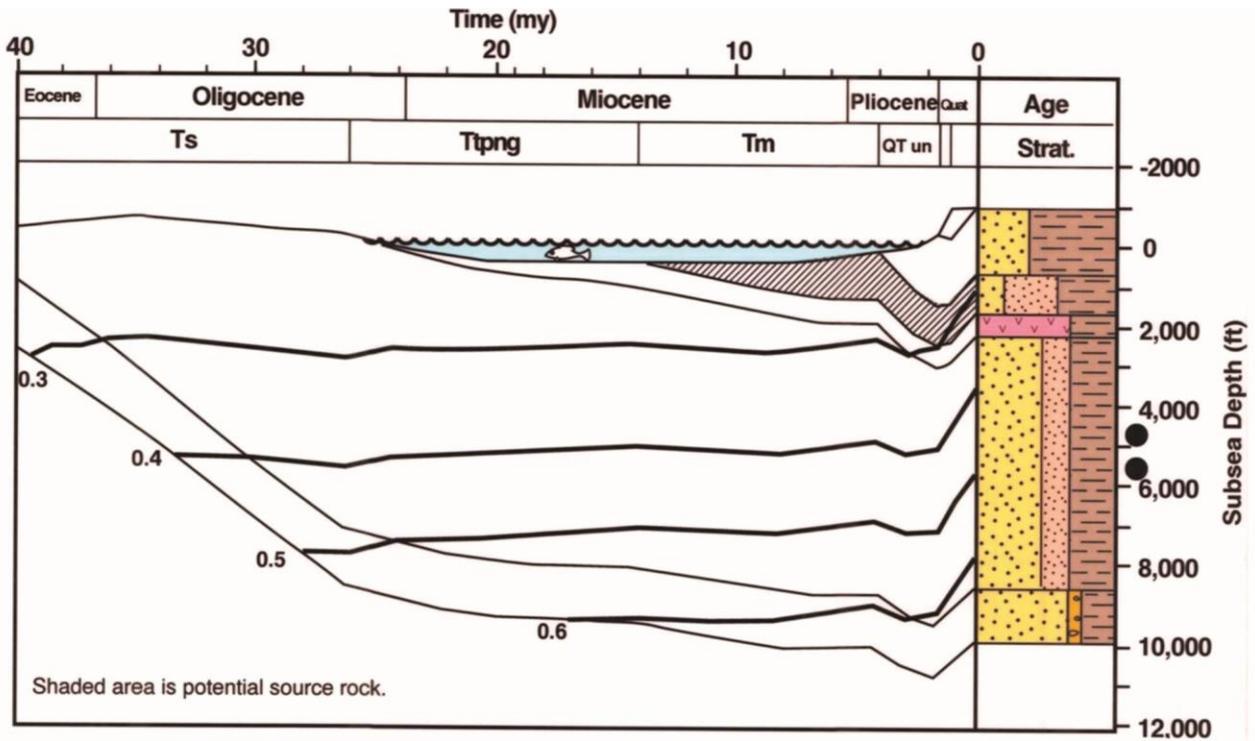
Figure 17A. South Mountain field burial history showing % Ro. Exxon #39 well and surface geology composite. Heat flow = 1.15 HFU calibrated with DeRito (1989) heat flow and Sespe AFT temperatures (Hathon, 1992).
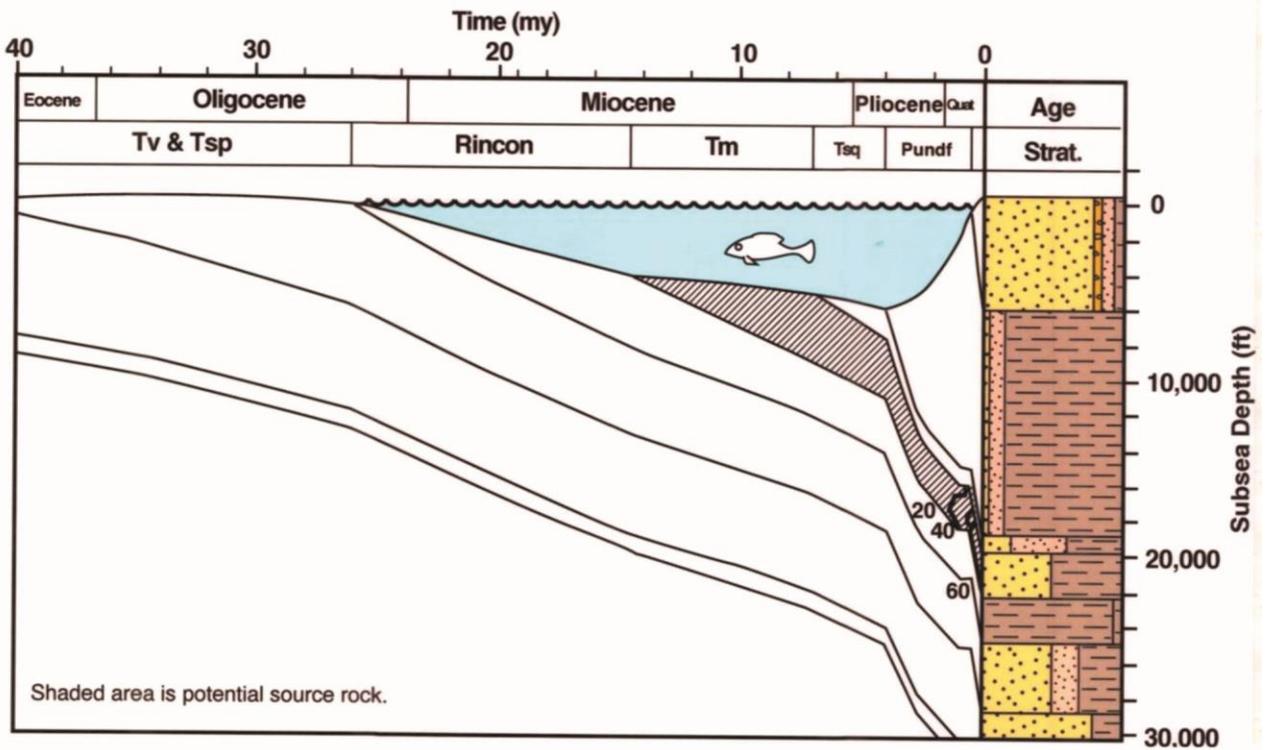
Figure 17B. Central Ventura kitchen burial history showing HC transformation ratio (%). Heat Flow = 1.1 HFU Sespe #6 well.

OIL GENERATION RATE
GAS GENERATION RATE

Generation Rate

20 18 16 14 12 10 8 6 4 2 0

0.0

Time (my)
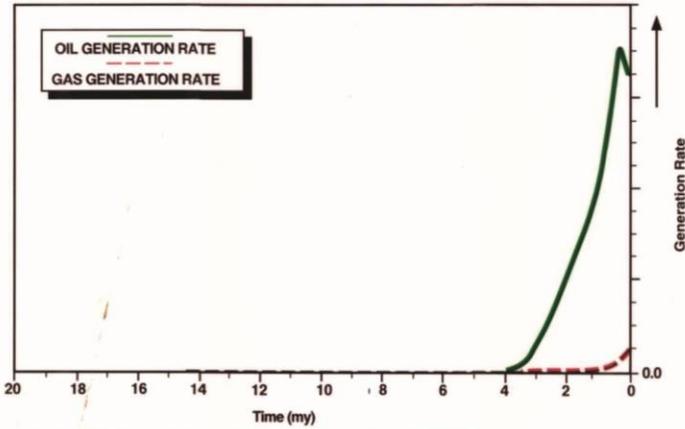
Figure 18A. Central Ventura kitchen lower Monterey HC generation rate versus time.
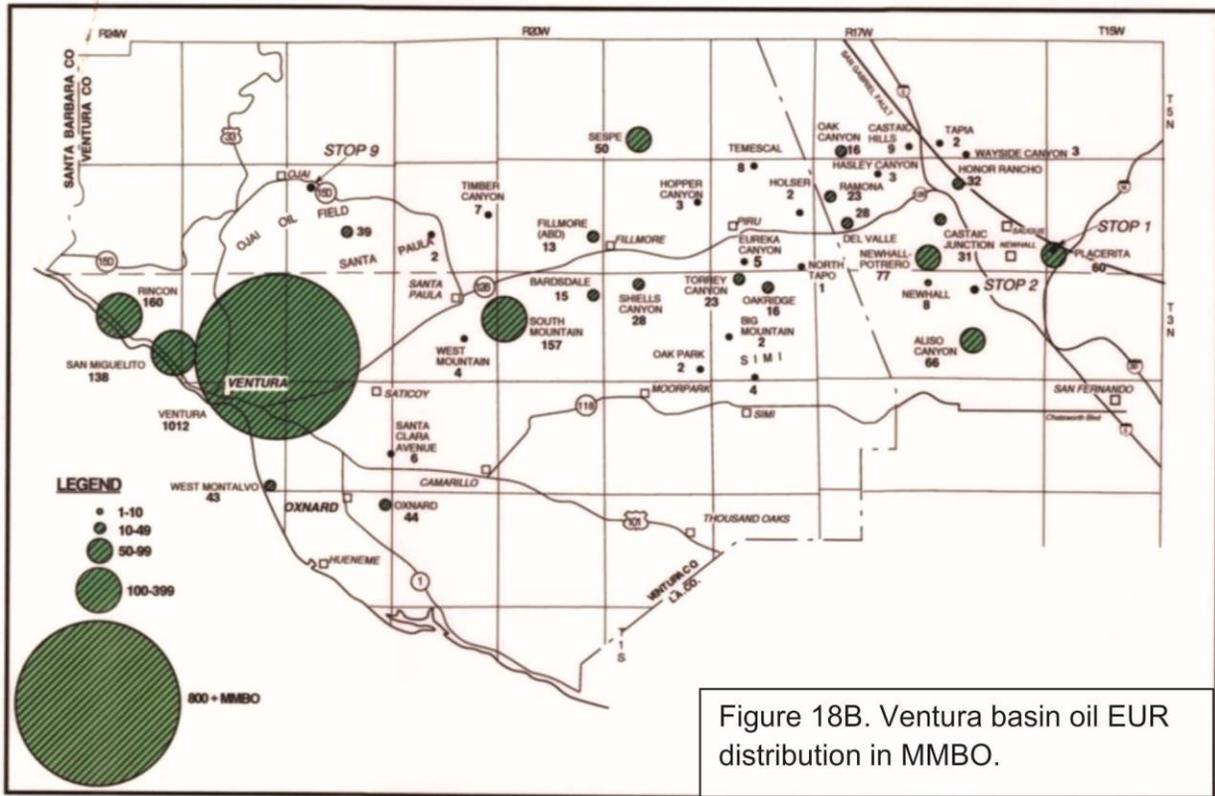
Figure 18B. Ventura basin oil EUR distribution in MMBO.

C29 Sterane Isomerization [20S/(20S+20R)]

Increasing Thermal Maturity

0.30   0.35   0.40   0.45   0.50   0.55   0.60   0.65   0.70

Early Oil Window

Mid & Late Window

S. Mountain (Sespe and Pliocene)

Yowlumne

Wheeler Ridge 23-27

equilibrium

Oils are low maturity

equilibrium

C32 Homohopane Isomerization [20S/(20S+20R)]

Increasing Thermal Maturity

○ San Joaquin-M
✕ Ventura
△ Santa Barbara
▽ Santa Maria
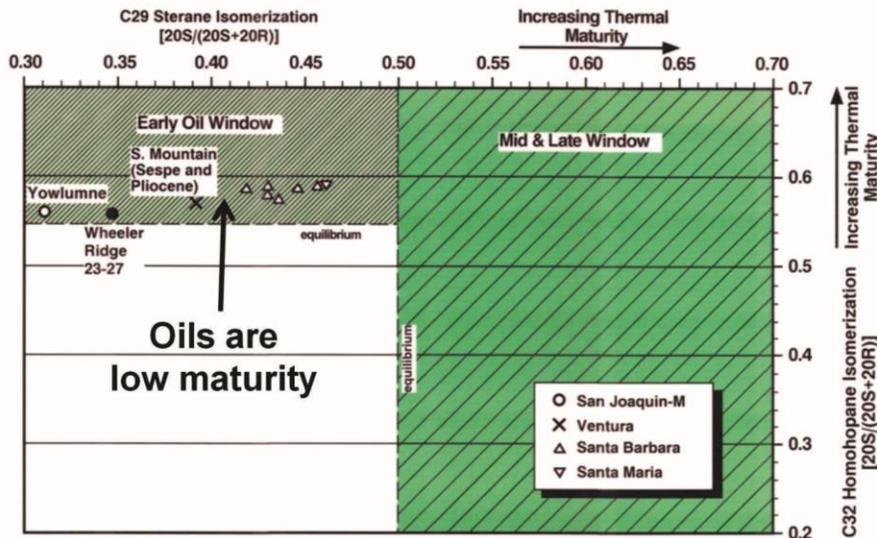
Figure 18C. Maturity of California oils including Yowlumne, Wheeler Ridge and South Mountain. Courtesy of Albert Holba, ARCO Exploration and Production Technology Company.

Directions from Stop #2 to Stop #3: Return to Hwy 150, turn right (west). Drive is along the north flank of Sulfur Mountain and numerous large tar steeps from the fractured Monterey Formation can be observed along the south side of the highway. Highway passes through upper Ojai Valley and descends towards Ojai and Stop #3 is on the left. Stop is in a wide parking area that is across the highway and near a blind curve. <u>__Please use caution when making a left turn into parking area.__</u>

Stop #3, Ojai Valley overview

Stop #3 is on Sespe Formation red beds along the north flank of the Lion Mountain anticlinal trend that is uplifted on the south-dipping Santa Ana fault   whose surface trace is along the southern margin of Ojai Valley (Figure 19). The Lion Mountain anticline plunges eastward under Upper Ojai Valley that we have just driven through. Small amounts of oil have been produced from the Coldwater Formation sandstone and sandstone within the lower Sespe Formation at the Lion Mountain area located about two miles west of this stop.

From this stop, looking northward across Ojai Valley is the south flank of the Topatopa Range (Figure 19). The various Eocene age formations are overturned to north dip with the Oligocene age Sespe Formation red beds exposed along the base of the range and this structure is well known, at least geologically, as the Matilija overturn. The overturn is the easternmost segment of a steeply folded panel of rocks that to the west is generally south-dipping. The panel consists of a thick sequence of Cretaceous and Tertiary formations composing the south flank of the Santa Ynez Mountains and extends from here to Point Conception (a distance of about 60 miles). Eastward, the Matilija overturn strikes towards a more complex series of smaller anticlines: Echo Canyon and Santa Paula Ridge, and several unnamed anticlines with overturned south limbs (Figure 11). The Matilija overturn is the frontal structure to the Santa Ynez Mountains anticlinorium that is shown in cross section 6-6' (Figure 20A).

Figure 19. Surface geologic map of the Ojai 7.5' quadrangles by T.W.Dibblee Jr. Paper Dibblee maps are available for purchase from the Santa Barbara Museum of Natural History: www.sbnature.org/dibblee/. Regional cross section 6-6' is shown in Figure 20.

Regional cross Section 6-6' (Namson, 1986):

Regional cross section 6-6' (Figure 20A) extends from the eastern end of the Santa Barbara Channel near Port Hueneme, crosses the Oak Ridge fault, the deep Pliocene age sedimentary trough of the Ventura basin, the Ventura Avenue anticline, Sulphur Mountain and Ojai Valley, Santa Ynez Range, Pine Mountain ridge, and ends at the Big Pine fault. The structural interpretation shown in cross section 6-6' is from Namson (1986 and 1987) where it first appeared in publication as cross section C-C' (Plate II in 1986 publication). Subsequently cross section 6-6' was incorporated into Namson and Davis's cross section across the entire western Transverse Ranges (Namson and Davis, 1988b) that received much negative commentary in print and vocally, for instance comments in Geology (1989). Namson and Davis (1988b plus comments and replies are reprinted at the end of this guidebook).

The section begins on a structural shelf just south of West Montalvo oil field which is part of the 60 km long Oak Ridge-Montalvo anticlinal trend. On the basis of the asymmetric shape of the anticlinal fold trend it is interpreted to be part of a north-vergent, fault-propagation fold above the postulated South Mountain thrust (Figures 9A & 12A). The Oak Ridge fault is the southern boundary of the deep Pliocene and Pleistocene age Ventura basin and the fault cuts the north limb of the anticlinal trend. As previously shown (Figures 10C-E) the Oak Ridge fault is interpreted to be a Pliocene age normal fault whose shallow portion has been rotated northward by the folding of Oak Ridge-Montalvo anticlinal trend. This extensive fold contains the anticlinal oil traps at Sheills Canyon, Bardsdale, South Mountain, and West Montalvo oil fields. Growth of the fold rotates the older Oak Ridge fault surface into a reverse fault at shallow levels and excess slip from the deeper South Mountain thrust has reactivated shallow segments of the Oak Ridge fault. Cross section 6-6' and Figures 10C-E show the Oak Ridge fault reactivation is deep in the West Montalvo-Oxnard Plain area and the potential for fault surface rupture is very low.

Cross section 6-6' (Figure 20A) shows Namson's deeper interpretation of the structural geometry and kinematic development of the southern margin of the deep Ventura basin and how that area is linked to convergent deformation to the north at Ventura Avenue anticline and the San Cayetano thrust system. Southward directed slip along the Lion Mountain detachment extends across the deep Ventura basin and cuts and translates the shallow portion of the Oak Ridge normal fault southward. Approximately 4.7 km of back slip coming off the Lion Mountain

detachment and up the South Mountain thrust creates a thrust wedge between the south-dipping thrust and the deeper detachment. Northward and deeper the 4.7 kms of offset of the Oak Ridge fault creates a structural shelf just below the Lion Mountain detachment and between the two portions of the older normal fault. This structural shelf along the southern margin of the deep Ventura basin and between the offset shallow and deep segments of the Oak Ridge fault is shown in the other regional cross sections by Namson to the east (Figures 9A & 12A). This structural shelf is a regional feature of the southern margin of the deep Ventura basin and extends eastward to at least the Aliso Canyon area of the eastern Ventura basin (Figures 3 & 6A). Aliso Canyon oil field (now a gas storage field) is located within the structural shelf shows the largely untested shelf trend may have additional exploration potential.

Regional cross section 6-6' crosses the Ventura Avenue anticline that is located along the northern margin of the deep Pliocene age trough of the Ventura basin (Figure 20A). The cross section shows Namson interpretation (1986) of the deep structure at Ventura Avenue anticline and the anticline's geometric and kinematic northward connection to the San Cayetano thrust system and the Lion Mountain fault that is exposed along the north flank of Sulphur Mountain and near Stop #3. In this interpretation the Ventura Avenue anticline is shown as a detachment fold above the Lion fault that is a detachment fault at the base of the Rincon Formation, and also a higher thrust flat to the San Cayetano thrust system. The Ventura Avenue anticline is shown to be folded and uplifted by a series of wedge-shaped imbricated thrust faults that step up from the Lion Mountain fault detachment surface. Under the Canada Larga syncline, that is just north of Ventura Avenue anticline, the lower splay of the San Cayetano thrust (SCT 1) intersects the Lion Mountain detachment to form a southward directed fault wedge in the front limb of the Lion Mountain anticline.

Subsequent to Namson (1986 &1987) and Namson and Davis (1988b) cross section publications Yeats, et al. (1988) recognized the importance of a detachment at the base of the Rincon Formation but renamed it the Sisar detachment and rooted it southward across the deep Pliocene trough of the Ventura basin and into the Oak Ridge fault system. This interpretation is not restorable nor viable. A subsequent and very different interpretation of the Ventura basin by Huftile and Yeats (1995) closely resembles Namson's original 1986 interpretation (compare Figures 20A and 20C).

North of the Ventura Avenue anticline is the Lion Mountain anticline that is interpreted to be a fault-bend fold associated with a ramp on a splay of the lower splay of the San Cayetano thrust system (SCT 1) which steps up from a lower detachment within the Cretaceous strata to the mid-level detachment at 8 km depth. Total slip going up the ramp is 16.1 km and slip transferred to the mid-level detachment is reduced to 10.3 km with 5.7 km of slip consumed by folding. Approximately 1.8 km of slip is consumed in the Ventura Avenue anticline and 4.7 km of slip in the anticlinal West Montalvo oil field. The 3.8 km slip differential is interpreted to come to the surface as a back thrust on the Lion Mountain fault.

North of the Lion Mountain anticline and Ojai Valley are the Santa Ynez Mountains anticlinorium-a complexly folded structure. The overall structure is asymmetric and south vergent with a steep to overturned south limb. The crest of the anticlinorium is deformed by several small folds and the north limb of the anticlinorium dips moderately. The anticlinorium is the result of two phases of deformation one during the late Eocene and early Oligocene (Ynezian orogeny) and the other during late Cenozoic time (Namson, 1987). The late Cenozoic deformation is interpreted to be a combination of a fault-bend fold and a fault-propagation fold. The fault-bend fold is related to a ramp in the lower splay of San Cayetano thrust (SCT 1) from the basal detachment at about 12 km depth to an intermediate upper detachment in the lower part of the Cretaceous section. The slip on SCT 1 is 17.7 km which is transferred southward into the thrust ramp causing the Lion Mountain anticline. The shallow level fault-propagation fold above the upper splay of the San Cayetano thrust fault (SCT 2) has 3.3 km of slip. This shallow level folding has deformed the older Santa Ynez fault and is interpreted to be a north-vergent back thrust associated with a south-vergent Oligocene thrust system that uplifted the ancestral San Rafael Mountains (Reed and Hollister, 1936). The Santa Ynez fault is folded and cut by splays off the San Cayetano thrust system.

In the vicinity of the Pine Mountain ridge there are two anticlines: one in the hanging wall and one in the footwall of the Pine Mountain fault. The asymmetric fold in the footwall of the Pine Mountain thrust is interpreted to be a fault propagation fold associated with a thrust that ramps up from an intermediate detachment at the top of the Cretaceous section and terminates at the synclinal axis within Eocene strata. Slip on this thrust is 3.5 km. The Pine Mountain fault is

interpreted to be a splay that ramps up across the back limb of the fault-propagation fold. The slip on the Pine Mountain fault is 2.4 km.

The present-day length of the cross section is 67.6 km and the restored cross section is 99.0 km which yields 31.4 km of convergence (Figures 20A & B). The convergence rate from Port Hueneme to the Pine Mountain fault is 7.9-15.7 mm/yr., assuming convergent deformation started between 2.0 and 4.0 Ma.

Directions from Stop #3 to Stop #4: *From stop #3 continue downhill on Hwy 150 through the Ojai Valley and town of Ojai. Near western edge of Ojai Hwy 150 will intersect with Hwy 33- continue straight, do not turn. Road is now Hwy 33 and 150 for a short distance and we will remain on Hwy 33 towards Stop #4. Hwy 33 is headed south along the east side of Ventura River. We will exit Hwy 33 at Casitas Vistas Road (Foster Park) exit. Go left under Hwy 33 overpass and turn right on to Ventura Avenue. Proceed south to Ventura Avenue Anticline oil field. Stop #4 is near crest of anticline.*
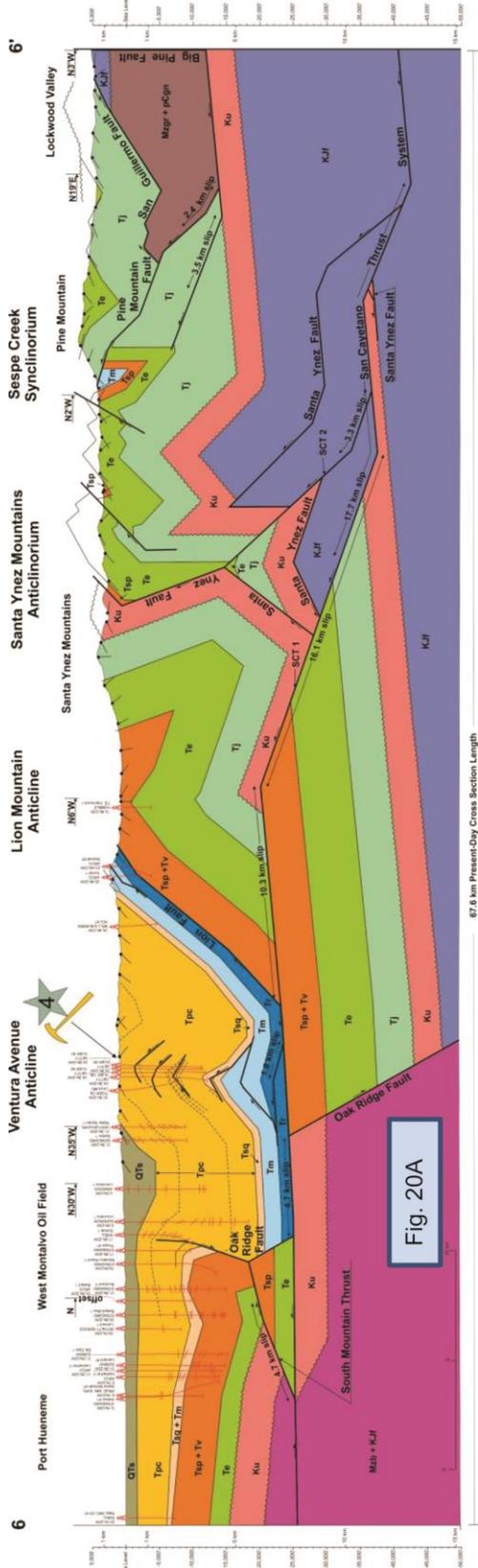
Figure 20A. Cross section 6-6' (Namson, 1986, 1987) from Port Hueneme to the Big Pine fault. See Figure 12A for rock unit abbreviations.
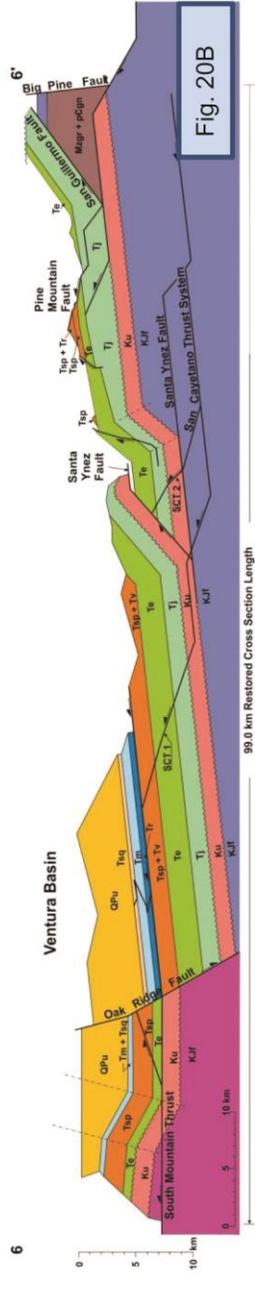
Figure 20B. Cross section restoration yields 31.4 km of convergence. The convergence rate from Port Hueneme to the Pine Mountain fault is 7.9-15.7 mm/yr., assuming convergence deformation started between 2.0 and 4.0 Ma.

Figure 20C. Yeats, et al. (1988) cross section B-B' and kinematic cartoon showing Sisar decollement rooted into Oak Ridge fault, and Ventura Avenue anticline formed as a result of northward slip on the Sisar decollement.
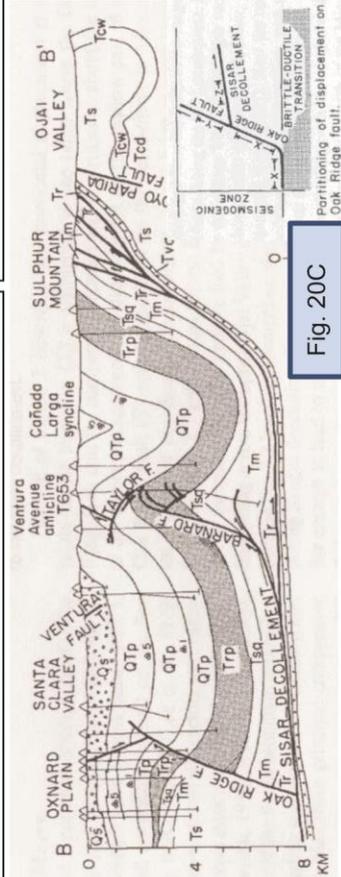
Figure 20D. Huftile and Yeats (1995) cross section B-B'. Yeats and Huftile (1989) were highly critical of Namson and Davis' 1989b interpretation and approach, but remarkably and seven years later, Huftile and Yeats (1995) published a similar interpretation.
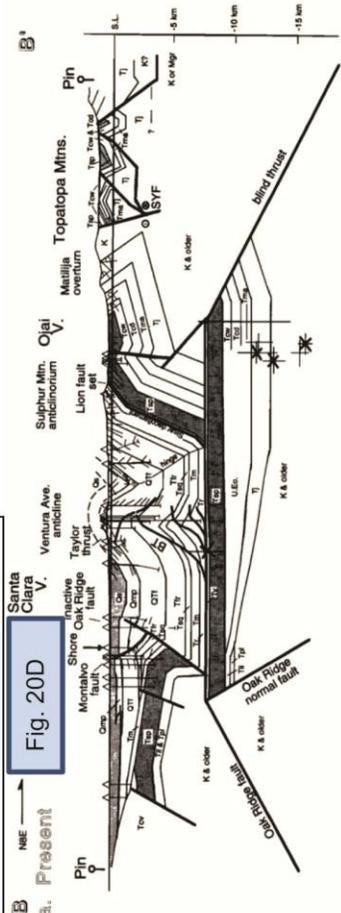
Stop #4, Ventura Avenue Anticline oil field

Geologic summary: Stop #4 is near the axis of the Ventura Avenue Anticline that at the surface has folded deep marine clastic deposits of the Pico Formation (Figure 21). To the north and across the Ventura River wash are north-dipping sandstone, siltstone, and shale of the Pico Formation. On the ridge above the Pico outcrops are red beds of the Sespe Formation that are thrust southward over the Pico beds by the Red Mountain fault. The Red Mountain fault is a major east-west trending, north-dipping, thrust fault just north of the Ventura Avenue anticlinal trend. Just to the east of the Ventura River wash the surface trace of Red Mountain fault bends northward towards the western termination of the Sulphur Mountain anticline, the fault's surface trace dies out in lower Monterey Formation beds. East of the Red Mountain fault Sespe, Vaqueros, and lower Monterey beds dip eastward towards the wide south limb of the Sulphur Mountain anticline. The Canada Larga syncline separates Sulphur Mountain and Ventura Avenue anticlines (Figures 21 & 22).

The Ventura Avenue anticline is a very large east-west trending fold between the Canada Larga syncline to the north and the thick Pliocene and Quaternary age Ventura basin trough to the south. Both anticlinal limbs have steep dips and in map view the north limb has a much narrower north-south extent than the south limb. The anticline has a steep east plunge into the Ventura trough where it terminates, but to the west the anticlinal structure continues for some distance into the offshore. Onshore the Ventura Avenue anticline traps the Ventura and San Miguelito oil fields, and westward the anticlinal trend continues and traps significant oil Cuadras (offshore accumulations in three culminations: Rincon (partially offshore), Carpinteria Offshore, and Dos Cuadras (offshore).

Figure 21. Surface geologic map of the Ventura-Pitas Point 7.5' quadrangles by T.W.Dibblee Jr. Paper Dibblee maps are available for purchase from the Santa Barbara Museum of Natural History: www.sbnature.org/dibblee/.

Figure 22. Surface geologic map of the Saticoy 7.5' quadrangles by T.W.Dibblee Jr. Paper Dibblee maps are available for purchase from the Santa Barbara Museum of Natural History: www.sbnature.org/dibblee/. Regional cross section 6-6' is shown in Figure 20.

Ventura Avenue oil field summary (summarized from Wright and Heck, 1987, DOGGR, 1992, Schwalbach, et al., 2009):

Discovery and history: In 1903 seven shallow gas wells were drilled and the gas was used by Ventura County Power Company. The State Consolidated Oil Company Lloyd #1 well was drilled in 1916 and flowed a small amount of 56 API gravity oil and a large amount of salt water and gas (months later the well blew out). The official discovery well is the Shell Gosnell #1, completed in 1919, with a total depth of 3498 feet, and initial production of 150 BOPD of 29 degree API oil. Associated Oil obtained the portion of the field east of the Ventura River and in 1930 began a successful development effort using rotary drilling and dense mud that was not possible earlier using cable-tool drilling.

Trap: Anticline with a complex internal structure consisting of a number of north and south dipping thrust faults that repeat and trap many of the oil reservoirs. Oil field is separated on the west from the San Miguelito oil field by a cross fault.

Reservoirs: Eight producing zones that range from 3,600 to 12,000 feet depth. Zones are sandstone in the Repetto and Pico Formation that range in age from early Pliocene to early Pleistocene, and are marine turbidite deposits that occur as "shoestring" depositional bodies in contrast to the more commonly recognized fan and sheet-like bodies of other locations (Hsu, 1977). In general the sand reservoirs have excellent lateral continuity in an east-west direction and thin to the north and south. Porosity ranges from 20% in the shallowest zone to 15% in the deepest zone. Permeability ranges from 48 MD in the shallowest zone to 9 MD in the deepest zone. The overall Repetto and Pico section is sand dominated and individual reservoirs are commonly separated by shale units that are interpreted to be flooding or abandonment surfaces that can act as pressure barriers.

Oil and gas: Oil gravity is 30 degree API and GOR from 550 to 800 (SCF/STB)

Volumes: Cumulative production as of 2009 was 998 MMBO and 2,056 BCFG.

Key references: Additional information on the Ventura Anticline oil field (also called the Ventura oil field) and adjacent area are in Hacker (1969), Nagle and Parker (1971), Hsu

(1977), Hsu, et al (1980), Yeats (1982a, b; 1983), Wright and Heck (1987), Sylvester and Brown (1988), DOGGR (1992), Huftile and Yeats (1995).

Directions from Stop #4 to hotel: *Continue south on Ventura Avenue. Turn right on Stanley Avenue. At Hwy 33 overpass take Hwy 33 south. At intersection with 101 Fwy take 101 south. Exit 101 at Seaward Avenue and make a left on to Harbor Blvd. Take Harbor Blvd past Ventura Harbor, cross Santa Clara River mouth, pass Oxnard Shores and turn right at Costa de Oro to Embassy Suites Mandalay Beach Hotel and Resort, 2101 Mandalay Beach Road, Oxnard, CA 93050*

END OF FIELD TRIP

Acknowledgements
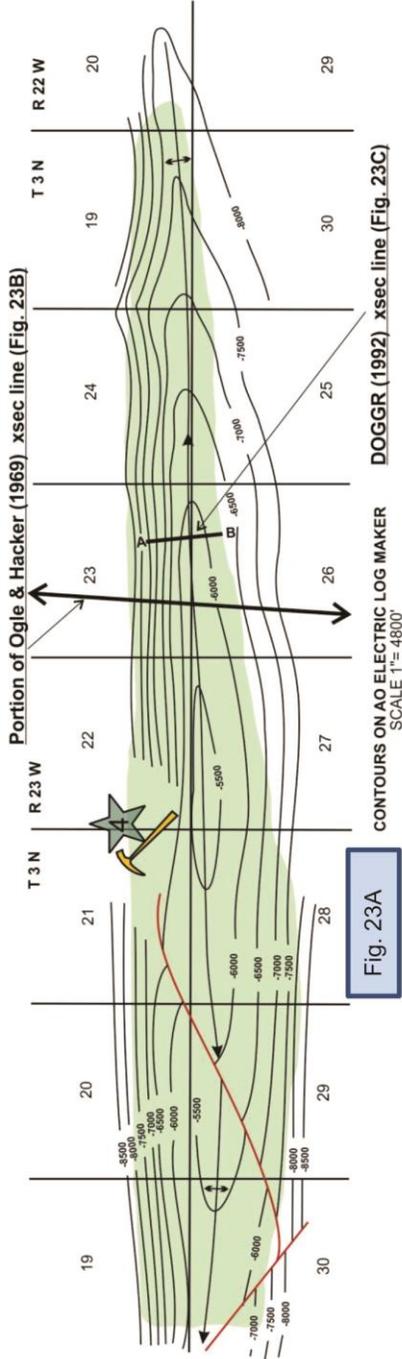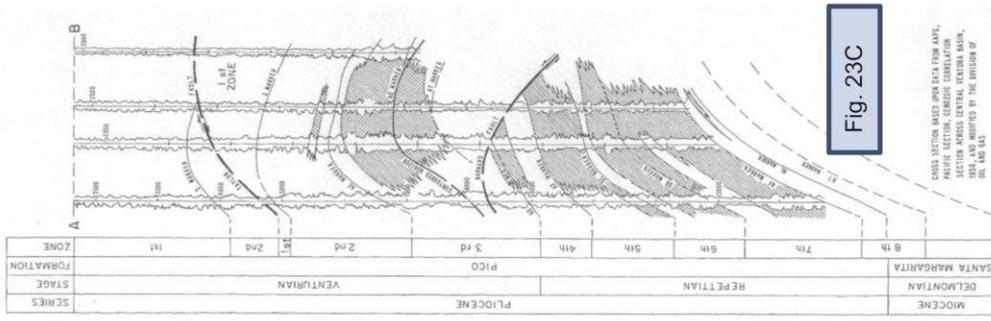
Figure 23C. Cross section of Ventura Avenue anticline and wells with elog curves (DOGGR, 1992). The subsurface axial region of the anticline is much more structurally complex than the surface mapping shows. The oil productive zone are cut and repeated by numerous north and south-dipping thrust faults that act as seals and possible oil migration pathways. Also note the sand-rich character of the reservoirs.
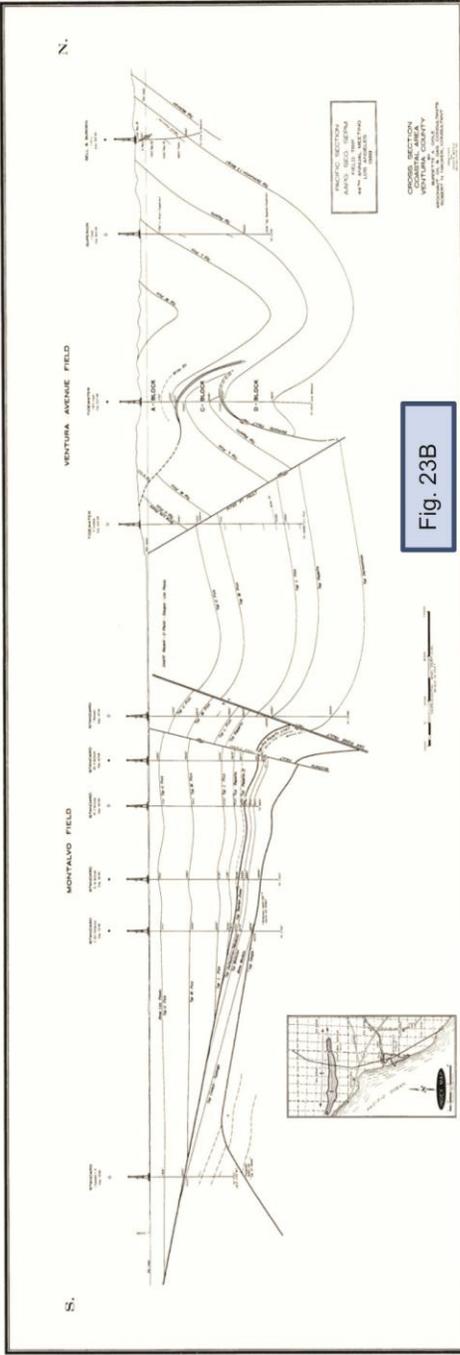
Figure 23B. North-south cross section from Ogle and Hacker (1969) shows the Ventura Avenue anticline, the Barnard fault, the postulated eastward continuation of the Pitas Point fault that is more recently called the Ventura fault, and the Oak Ridge fault. Hubbard ,et al., (2014) propose that the Ventura fault is capable of generating M~8 earthquakes, several meters of surface offset per seismic event, and the generation of tsunamis. Yeats (1982a, b) using additional well data, argued that the Ventura fault is insignificant and not active, and possibly nonexistent. Yeats points out that much of the data for an active fault are from surface or very shallow geologic investigations whose observations are open to various interpretations.

Figure 23A. Ventura Avenue oil field structure map on AO marker within the oil productive 3rd zone of the Pico Formation (DOGGR, 1992). Map is on the hanging wall block of the Barnard fault, and the AO zone and 3rd zone in footwall of the fault is also oil productive.

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