Field excursion: Petroleum traps and structures along the San Andreas convergent strike-slip plate boundary, California

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SUMMARY

Fault-related fold models that illustrate the geometry and kinematic development of petroleum traps and structures are frequently used to assist basin exploration and development of structurally complex oil fields. Worldwide, several petroleum-rich provinces are situated in convergent strike-slip settings with adjacent convergent structures that are commonly petroleum traps. Strain studies and modeling of these settings are dominated by the wrench fault model, and examples from the San Andreas fault plate boundary and its trapping influence on adjacent large oil fields in California abound (Wilcox et al., 1973). Use of this model in petroleum exploration and geologic education is problematic and can lead to poor choices and wasted drilling dollars. Here, we show at three field trip stops that the wrench model and its associated flower structures (Harding, 1976) and palm tree structures (Sylvester and Smith, 1976; Sylvester, 1988) fail to explain the oil trapping style and structure of the uppermost crust near the San Andreas fault (Figure 1).

The San Andreas transform fault through much of southern and central California is oblique to the direction of motion between North America and the Pacific plates, and two models have been used to explain the strain response to the stress field: (1) the wrench model that results from a high shear strength on the San Andreas fault and (2) strain partitioning along a weak San Andreas fault that is characterized by pure strike-slip and an adjacent belt of convergent structures that are parallel to subparallel to the San Andreas fault (Mount and Suppe, 1987; Zoback et al., 1987; Townend and Zoback, 2004). During the field trip, we present data and interpretations that support the strain-partitioned model that is characterized by a strike-slip San Andreas fault with no vertical offset and development of an adjacent and
coeval fold-and-thrust belt with convergent structures that have little or no strike-slip component (Namson and Davis, 1988a, b). Further, we show that application of geometric and kinematic models commonly used in fold-and-thrust belts, for example, fault-bend and fault-propagation folds (Suppe, 1983; Suppe and Medwedeff, 1990), provides a realistic, testable, and economically successful methodology for basin exploration and oil-field development in the convergent petroleum traps of southern and central California (Figure 1). A more optimistic view of this area’s oil and gas exploration potential is provided by the fold-and-thrust model, because the larger thrust sheets conceal footwalls with untested subbasins and structures with known oil source and reservoir rocks (Davis et al., 1988; Davis, 2015).

Other implications of using the strain-partitioned model combined with restorable cross sections

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**Figure 1.** Map of southern and southern-central California showing the three field trip stops, petroleum basins, oil fields, the San Andreas fault (SAF), and many of the regional cross section lines constructed by Namson and Davis since 1988. Oil fields are dominantly trapped by young, convergent structures that are the result of late Cenozoic transpression along the SAF plate boundary, which will be demonstrated at the field trip stops. Stop 1 is at the Wheeler Ridge oil field and the convergent San Emigdio Mountains, Stop 2 is along the western big bend segment of the SAF, and Stop 3 is at the Russell Ranch oil field and the convergent Caliente Range. The Neogene basins of southern California are very oil prolific (with a cumulative production of nearly 20 billion bbl of oil and daily production now at 560,000 BOPD). Much of the oil is sourced from the Miocene Monterey Formation, and basin modeling shows that only the deepest parts have recently reached sufficient depths for oil generation (Davis et al., 1996). Integration of basin modeling and cross section work shows a very young and active petroleum system with discrete generation pods within the deepest parts of the basins and trapping structures formed just before and during oil generation. Fuis et al. (2012) proposed that the SAF is dipping southwest from 55° to 75° through its western big bend segment based on deep geophysical data, and the southward dip supports the cross section interpretation of Namson and Davis (1988b) that the SAF is dipping southward as shown in Figure 2A. However, it is unclear to us at this time if the SAF dips southwest under the Cuyama basin and Carrizo Plain as mapped by Fuis et al. (2012). Cross sections 1–15 are available at [www.thomasldavisgeologist.com](http://www.thomasldavisgeologist.com) (Nameson and Davis, 1996), and many are cataloged as National Earthquake Hazards Reduction Program–US Geological Survey (USGS) Final Technical Reports, USGS Open File Reports.
Figure 2. (A) Structural transect across the western Transverse Ranges (modified from Namson and Davis, 1988b). Note southward dip of San Andreas fault (SAF) that is required by restoration of the Pleito thrust system. (B) Line-length restoration of late Pliocene through Quaternary compressive structures along cross section (modified from Namson and Davis, 1988b). Restoration shows late Eocene and Oligocene convergence (Ynezian orogeny), Miocene and Pliocene normal faults, and SAF strike-slip offset. The SAF restores to a vertical fault, separating terrain now offset horizontally approximately 100 km (62 mi) since late Pliocene. (C) and (D) Schematic cross sections showing how shortening above the brittle-ductile transition is caused by subduction of the lower crust and lithosphere of the Pacific plate and the shallow part of the plate boundary is translated over the leading edge of the North American plate (modified from Namson and Davis, 1988b). (C) Shows the edge of the North American plate as a vertical buttress to deformation. (D) Shows the leading edge of the North American plate as a crustal-scale wedge driven into the Pacific plate. Circled A (away) and T (toward) indicate strike-slip motion of the SAF in and out of plane of section. CCF = Caballo Canyon fault; Fm = Formation; LF = Lion Fault; LMA = Lion Mountain anticline; MTN = Mountain; 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; SL = sea level; 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.
Figure 3. (A) Cross section across the San Emigdio Mountains (Mtns) and southern San Joaquin basin showing a fold-and-thrust interpretation of late Pliocene and Quaternary, north-directed convergence. The cross section integrates surface geology and well data and shows that the thrust faults of the Pleito thrust system (PTS) flatten with depth and ramps in the thrust fault surfaces make fault-bend and fault-propagation folds. The long, hanging-wall thrust flats at the base of the Temblor Formation (Fm) (Tom) and within the Eocene formations (Teo) indicate that the PTS intersects the San Andreas fault (SAF) at a high angle and show that the SAF and PTS merge into a south-dipping strike-slip fault (Namson and Davis, 1988b; Fuis, et al., 2012). The White Wolf fault (WWF) is interpreted to be an older normal fault that formed the edge of the Tejon depocenter (deep portion of southern San Joaquin basin) during the Miocene and Pliocene. A normal fault interpretation is preferred, because both sides of WWF were subsiding with respect to sea level (SL), with the northern side subsiding at a faster rate, as shown by coeval growth strata. The shallow part of the WWF was subsequently folded into a reverse fault geometry by growth of a fault-propagation fold associated with late Pliocene and Quaternary movement on the deeper Tejon thrust (TT). T v = volcanic and shallow-level intrusive rocks of the Tecuya and Temblor Formations. (B) A migrated two-dimensional seismic line image across the Cuyama basin, Caliente Range, and Carrizo Plain and adjacent to the SAF. The well shown and its updip redrill are the ARCO 1 Drake Federal that confirmed the position of the Morales thrust (MT) and the stratigraphy on the seismic line, and the well encountered the top of crystalline basement near total depth (TD; 17,193 ft [5240 m] measured depth). The image shows that reflectors from the MT flatten toward the SAF (located 1.2 mi [1.9 km] northeast of the end of the line), that the Caliente Mtn anticline (CMA) and Well Ranch syncline (WRS) are underlain by the thrust, and that beneath the anticline/syncline pair and thrust is a thick sequence of reflectors suggestive of a concealed basin whose existence was confirmed by subsequent drilling. T v = Vaqueros Formation. (C) A US Geological Survey (USGS) cross section adjacent to and roughly parallel to the seismic line in (B) shows a steepening-with-depth Morales fault that dips toward the SAF (Vedder, 1970; Vedder and Repenning, 1975). The well and seismic data developed by ARCO show the additional exploration potential of the Cuyama basin that is absent in the USGS interpretation. Wells shown on cross section are 1 = Richfield Oil Co. 1 Schaefer, TD = 8630 ft (2630 m); 2 = Richfield Oil Co. C-5 Russell, TD = 9808 ft (2989 m); 3 = Richfield Oil Co. C-2 Russell, TD = 12,981 ft (3957 m); 4 = Richfield Oil Co. C-1 Russell, TD = 2748 ft (838 m); 5 = C. W. Colgrove 53-4 Sawyer, TD = 1399 ft (426 m); 6 = Westates 2 Graham et al., TD = 2612 ft (796 m); 7 = International Exploration Co. 1 Evelyn, TD = 2452 ft (747 m); 8 = C. G. Lewis Oil Development Assoc. 1 Lewis, TD = 2320 ft (707 m); 9 = Texas Co. KCL Traver, TD = 5999 ft (1828 m). Horizontal scale and vertical scale are equal. CS = Cuyama shelf; CPA = Carrizo Plain anticline; Kgr = granitic rocks; KJf = Franciscan Assemblage; KJop = Coast Range Ophiolite; Kto-gn = tonalite and mafic-rich gneiss; Mzgr = granitic rocks (includes older gneissic rocks); Mzms = metasedimentary rocks; Mzrs = Rand Schist; Qa = Active stream deposits; Qf = Deformed alluvial deposits of Padrones Canyon; Qn = Deformed alluvial deposits; Qoa = Older alluvium; Qtp = Paso Robles Formation; Qtr = Older talus and rodslide deposits; QTu = Paso Robles Formation; QTu + Tes = Tulare, San Joaquin, and Etchegoin (Chanac) Formations; Qya = Younger alluvium; RNF = Rinconada Nacimiento fault; Tb = basalt flows and dikes; Tb1/Tb2/Tb3/Tb4/Tb5 = Basalt Flows; Tbc = Branch Canyon Sandstone; Tbs = Branch Canyon Sandstone and Santa Margarita Formation, undifferentiated; Tbw/Tbw1 = Bitterwater Creek Shale; Tc/Tcu/Tcc/Tcl/Tc2/Tc3/Tc4/Tc5 = Caliente Formation; Tcb = Caliente Formation and Branch Canyon Sandstone, undifferentiated; Tcy = Tecuya Formation; Ti = Intrusive igneous rock; TKu = Upper Cretaceous and lower Tertiary strata; Tm = Monterey Formation; Tmo = Morales Formation; Tmu = Monterey Shale; Tp = Pattiway Formation; Tpc = Quail Canyon Sandstone Member of the Vaqueros Formation; Tpr/Tpr1 = Painted Rock Sandstone Member of the Vaqueros Formation; Tq = Quatal Formation; Ts/Tsa = Simmler Formation; Tsm = Santa Margarita Formation; WRT = Wheeler Ridge thrust.
include the enhanced understanding of the deeper structure of the plate boundary and of seismic risk evaluation (Namson and Davis, 1988b). As shown at Stops 1 and 3, large thrust fault systems do not steepen with depth into the San Andreas fault but have listric shapes and must intersect the San Andreas fault at a high angle (Figure 2A). In our interpretation, the San Andreas fault and the thrust systems share a common displacement surface that dips at low angles and offsets the shallow plate boundary from its deeper continuation. In the western big bend segment of the San Andreas fault, this displacement surface is a south-dipping fault that has accommodated both right lateral strike-slip on the San Andreas fault and north-directed convergence along the Pleito thrust system during the late Cenozoic (Namson and Davis, 1988b). Fuis et al. (2012), unaware of the work of Namson and Davis (1988b), proposed that the San Andreas fault is dipping southwest from 55° to 75° along the western big bend segment based on studies of potential field data, active-source imaging, and seismicity. Large strike-slip faults with low-angle fault surfaces are not prevalent in the geologic literature but have been observed (Umhoefer et al., 2007).

The western big bend segment of the San Andreas fault is not the cause of north–south shortening, because shortening continues well to the west of the bend. In our interpretation, the north–south shortening in the western Transverse Ranges is driven by deeper processes in the lithosphere and asthenosphere (Figure 2C, D) and not caused by constraining bend geometry as proposed by many. Instead, the bend results from the north–south shortening and deformation of the fault’s trace, and the shallower part of the San Andreas fault plate boundary is offset and translated north- and northeastward over the leading edge of the North American plate. A line-length restoration of late Pliocene through Quaternary convergent structures across the Transverse Ranges yields 53 km (33 mi) of shortening (Figure 2B) and requires 53 km (33 mi) of crustal thickening or incipient subduction to balance shortening above the detachment (Figure 2C, D). Incipient subduction seems favored, because a 60-km-thick (37 mi) slab, shown by seismic tomography, extends to approximately 120 km (75 mi) depth and is coincident with a high-velocity anomaly in the western Transverse Ranges (Humphreys et al., 1984).

### STOPS

Stop 1 (35.005061°N, 118.986575°W) is at the Wheeler Ridge oil field (~59 million bbl of oil cumulative as of 2009) that is an actively growing anticline located along the deformational front of the San Emigdio Mountains and the southern end of the oil-prolific San Joaquin basin (Figure 1). To the south are the San Emigdio Mountains, a fold-and-thrust belt that is bounded on the south by the western big bend segment of the San Andreas fault. The proximity of the bend to the San Emigdio Mountains and the Wheeler Ridge oil-field trend (that includes north Tejon, Pleito, and White Wolf fields) provides an excellent area to evaluate the structural geometry, kinematics, and associated oil-field trapping mechanisms adjacent to a large strike-slip fault with associated convergent structures.

Pliocene and Quaternary uplift of the east–west-trending San Emigdio Mountains across the northwest-trending depositional strike of the San Joaquin basin provides a unique, natural cross section of a basin from nonmarine deposits in the east to deep-marine deposits in the west. Abundant surface exposures and well data provide mapping control of the stratigraphic trends and reveal fault-piercing points in the hanging wall and footwall of the Pleito thrust (“sensu stricto”) that indicate little or no lateral displacement despite its nearby proximity to the San Andreas fault. The lack of lateral offset shows that the positive flower-structure model with oblique-slip convergent faults cannot account for the folding and thrusting and uplift of the San Emigdio Mountains (Davis et al., 1996). The east–west trend of the fold axes and thrust faults indicates north–south-directed shortening, and the absence of lateral slip allows for north–south cross sections (Figure 3A) to be retrodeformed in their two-dimensional plane (Figure 2B) and dismisses the criticism that cross sections adjacent to the San Andreas fault cannot be retrodeformed because of strike-slip in and out of the cross section plane. Since the late 1980s, construction of oil-field cross sections using fault-bend and fault-propagation fold models constrained by matching hanging wall and footwall cut offs and flats has provided a better understanding of the movement history and geometry of the oil-trapping White Wolf fault and Wheeler Ridge thrust. The interpretation that the upper
segment of the older White Wolf normal fault has been rotated by deeper and younger folding and offset by the younger Wheeler Ridge thrust (Davis et al., 1996; Gordon and Gerke, 2009) has assisted in making deeper pool discoveries and provided key information about untested traps, including their potential to have cross-fault traps as well as the thickness of oil column.

Stop 2 (34.864257°N, 119.248282°W) is at Apache Saddle, which is located at the head of Santiago Canyon and within the western big bend segment of the San Andreas fault (Figure 1). With the exception of the pressure ridges, a tectonic geomorphic feature abundant within the fault zone, there is no evidence of vertical displacement along this segment of the fault. One of deepest exposures of the San Andreas fault zone is at Apache Saddle, and detailed mapping shows that the internal structure of the larger composite pressure ridges has a geometry similar to a positive flower structure (Davis and Duebendorfer, 1987). The southern side of the San Andreas fault zone is dominated by the Apache Saddle fault and its upper plate, which steepens with depth into Santiago Canyon and merges with the San Andreas fault. The steepening of the Apache Saddle fault into the San Andreas fault and the incohesive fault material within the upper plate of the Apache Saddle fault are the result of material faulted upward and outward from the fault zone. Along the fault zone are numerous pressure ridges that have an en echelon map pattern, and the ridges probably result from simple shear during fault offset. These ridges are confined to the fault zone, consist mostly of incohesive fault rock, and have no relationship to the many map-scale anticlines and convergent faults exterior to the fault zone, some of which are the large petroleum traps found along the southwestern margin of the San Joaquin basin.

Stop 3 (35.000699°N, 119.824675°W) is in the Cuyama oil basin (Figure 1), near the base of the Caliente Range, and along the southwestern edge of the Russell Ranch oil field (~70 million bbl of oil cumulative produced as of 2009). The range consists of two large, southwest-vergent anticlines bounded on the south and southwest by the surface traces of the Morales and Whiterock thrusts, which belong to the northeast-dipping Morales thrust system. To the northeast and on the other side of the range, out of view but nearby, are the Carrizo Plain and the San Andreas fault.

The thickest and most stratigraphically complete part of the Cuyama basin is within the Caliente Range and was thrust southward over the thinner and stratigraphically equivalent units of the “Cuyama shelf,” resulting in “basin inversion.” A dip seismic line (Figure 3B) shows the position and listric shape of the Morales fault that is consistent with the drilling results of the Atlantic-Richfield Company (ARCO) 1 Drake Federal well. The seismic image shows the various splays of the Morales thrust system root into a horizontal detachment at approximately 4 km (2 mi) depth beneath the surface expression of the Wells Ranch syncline; the detachment is a footwall flat, and its geometry, depth, and line length are required to match the hanging wall flat observed beneath the Caliente Range. Overthrusting has concealed a previously unknown and extensive part of the Cuyama oil basin. The presence of this subthrust basin, with known source and reservoir units, was suggested by seismic lines and balanced cross sections and proven by subsequent drilling of the ARCO 1 Stone well (Davis et al., 1988). A US Geological Survey cross section (Figure 3C) adjacent to and subparallel to the seismic image shown in Figure 3B interprets the Morales thrust to dip steeply under the Caliente Range and toward the San Andreas fault, and the structural style is typical of many southern and central California cross sections that adopt the flower-structure model when interpreting convergent fault geometry at depth. The additional well and seismic data developed by ARCO and combined with fault-related fold models and restorable cross sections show the additional exploration potential of the Cuyama basin that is absent in a flower-structure interpretation.

CONCLUSIONS

The North American/Pacific plate boundary has been strain partitioned during the late Cenozoic, with strike-slip motion taken up along the San Andreas fault and convergence taken up by adjacent fold-and-thrust belts with little or no strike-slip. Fault-related fold models and cross section constraints commonly used in fold-and-thrust belts provide a testable method for exploration and oil-field development in southern and central California. This method yields a more commercially successful approach to understanding known oil-field traps, and
offer a more optimistic view of southern and central California’s oil and gas exploration potential, because the larger thrust sheets conceal extensive footwall areas with untested structures. As shown in the oil-prolific southern San Joaquin (Stop 1) and the Cuyama basins (Stop 3), and contrary to the conclusions of Wilcox et al. (1973), Harding (1976), and Sylvester (1988), positive flower structures fail to explain the structural style and evolution of the basins and the geometry and kinematics of the numerous petroleum traps. Pressure ridges that probably result from simple shear and resemble positive flower structures are only found within the narrow San Andreas fault zone, but such ridges are not petroleum traps nor do they develop into the numerous petroleum traps adjacent to the San Andreas fault. Our regional interpretation of the San Andreas fault plate boundary along its western big bend segment requires that a horizontal detachment or a low-angle fault accommodates both strike-slip and convergent movements (Namson and Davis, 1988b), that the bend is a result of shortening and is not causing shortening, and that the shallow plate boundary is being offset and translated over the leading edge of the North American plate (Figure 2C, D).

REFERENCES CITED


Vedder, J. G., 1970, Geologic map of the Wells Ranch and Elkhorn Hills quadrangles showing juxtaposed Cenozoic rocks
along the San Andreas Fault, San Luis Obispo and Kern Counties, California: US Geological Survey Map I-585, scale 1:24,000, 2 sheets.

