Subsurface Evidence for the Puente Hills and Compton-Los Alamitos Faults in South-Central Los Angeles

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Abstract

We analyzed well data in the vicinity of a deep exploration campaign in 1973-1975 by American Petrofina Exploration Co. to a maximum depth of 6,477 m (American Petrofina Core Hole 1), twice the depth of data from multichannel seismic profiles used in previous studies. The deeper control of the Compton-Los Alamitos (CLA) and Puente Hills reverse faults based on these wells provides evidence of reverse faulting based on repetition of strata on electric logs, abrupt changes of dipmeter-based attitudes, and offset of events on seismic profiles following Avalon Boulevard and Vermont Avenue. Structure contours on the Puente Hills fault are straightforward, whereas contours on the CLA fault are more complex. The presence of faulting at depth leads to the conclusion that the CLA and Puente Hills reverse faults change upward into fault-propagation folds rather than fault-bend folds. The CLA fault marks the northeastern boundary of a broad anticline, called here the Central Uplift anticline, cut along its crest by the right-lateral strike-slip Potrero fault in the vicinity of our study. Structure contours at depth confirm the observations of others that the CLA fault swings westward and steepens in dip toward the NIFZ south of Inglewood oil field. The presence of reverse-fault-plane solutions along the northern NIFZ and evidence for uplift along the CLA fault east of Long Beach and Seal Beach oil fields during the 1933 Long Beach earthquake support an interpretation of faulting along the Newport-Inglewood trend related to strain partitioning, indicating that the NIFZ might generate a Coalinga-type reverse fault as well as a strike-slip event similar to the 1933 earthquake.

Introduction

In 1973-1975, American Petrofina Exploration Company undertook the last major petroleum exploratory project in Los Angeles (LA). The objective was the turbidite sandstone sequence in the deep LA trough, which was interpreted as bounded on the northeast and southwest by reverse faults, trapping a turbidite sandstone sequence in their respective footwalls that is equivalent to the major oil-producing strata of the LA basin. This view of opposing reverse faults extending to depth, on which the exploratory campaign was based, is illustrated by Wright (1991, his figure 8c and 9), and by Davis et al. (1989), who referred to the southwestern fault as the Compton fault and the northeastern fault as the Elysian Park fault. The sequence had been imaged by multichannel seismic profiles, although as is stated below, features labeled as faults in some cases are growth triangles in a dipping fold panel. The southern fault had been tested in 1958 by the Union-Chevron Pacific Electric wildcat well, and the northern fault had been penetrated in 1966 by Union-Standard Oil La Tijera EH-1 well. The American Petrofina exploratory campaign was unsuccessful, and the holes were abandoned.

On 1 October 1987, the Whittier Narrows earthquake of M_w 6 (Hauksson et al., 1988) was located on a fault subsequently called the Puente Hills thrust (Shaw and Shearer, 1999; Shaw et al., 2002). This earthquake fault did not rupture to the surface, although it did generate a broad anticline above the mainshock (Lin and Stein, 1989). The Whittier Narrows earthquake joined a newly-recognized class of earthquakes in which the surface expression is by folding (*cf.* Stein and Yeats, 1989). Shaw et al. (2002), based on work by Shaw and Shearer (1989) and Shearer (1997), constructed a cross section through the mainshock and Santa Fe Springs oil field that incorporated well data, seismic reflections of bedding and the north-dipping fault-plane, and distribution of aftershocks relative to the mainshock fault-plane solution to reveal a moderately-dipping thrust fault (Puente Hills thrust) to depths of 15 km. Shaw et al. (2002) divided their Puente Hills thrust into the Santa Fe Springs segment, on which the Whittier Narrows earthquake occurred, the Coyote Hills segment to the east (Myers et al., 2003), and the Los Angeles segment to the west, including the Las Cienegas and Elysian Park faults (Figure 1; Davis et al., 1989; Schneider et al., 1996; Tsutsumi et al., 2001). The three segments are

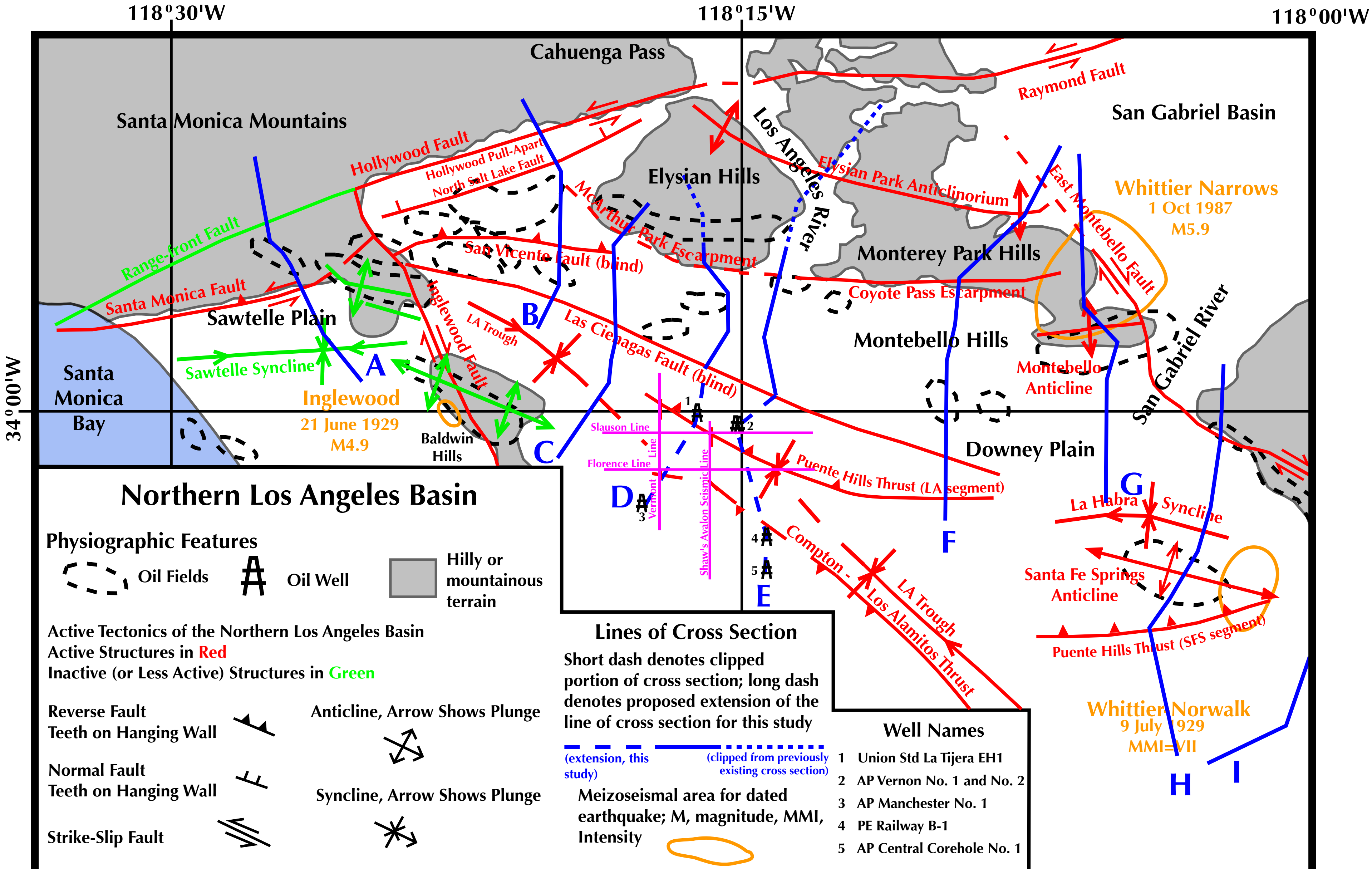

Figure 1

Index map of LA trough and vicinity showing major structures with the locations of extended cross-sections D and E in this report

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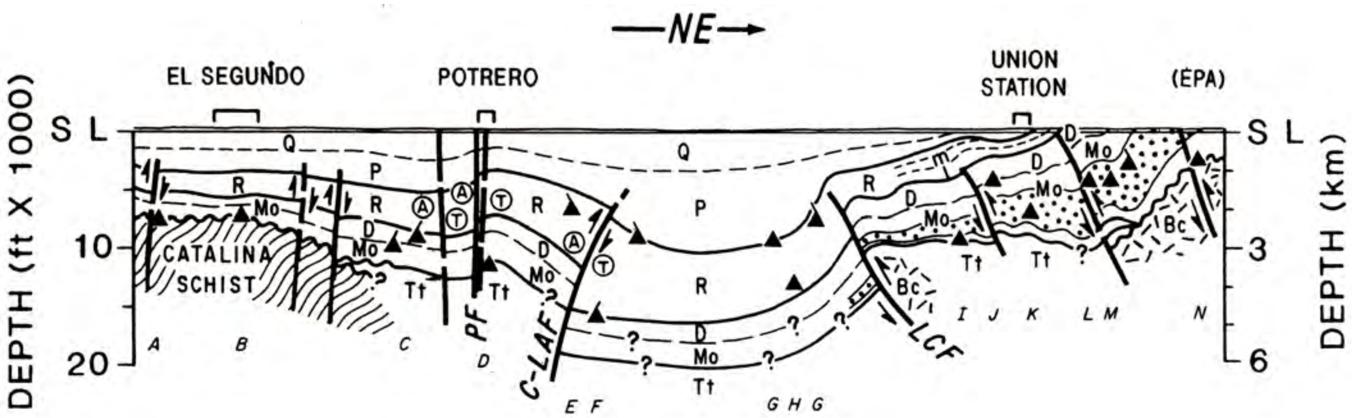
offset laterally, although it is unclear if there was once an unfaulted thrust, or if the three segments developed in their present position.

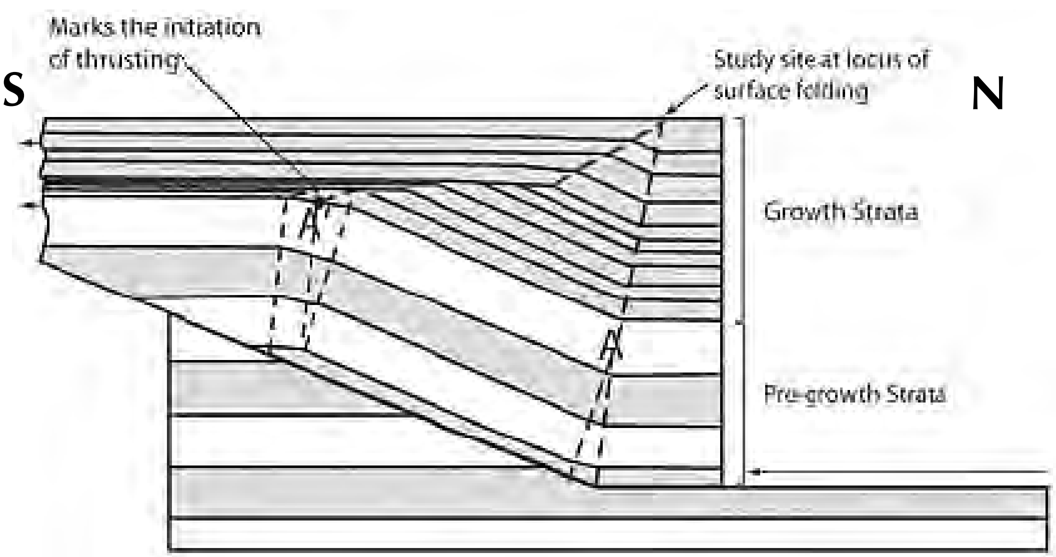
The incorporation of seismic-reflection and well data into an earthquake hazard analysis based on the 1987 earthquake led to a new interpretation based on fold theory (Figure 2B). The blind reverse faults of south-central LA, including the Compton-Los Alamitos (CLA) fault of Wright (1991) and the Los Angeles segment of the Puente Hills thrust of Shaw et al. (2002), were reinterpreted as low-angle structures derived by fault-bend folding (Shaw and Suppe, 1996), following a protocol developed by Suppe (1983). Both the southwest-dipping and northeast-dipping flanks of the central LA trough overlie the Elysian Park and CLA thrust ramps, respectively, of a regional Central Basin décollement, with a flat-lying deep trough between the two thrust ramps. The dipping panels above the ramps are narrower upsection, an expression of displacement on the thrust ramps, decreasing to zero at the surface if the ramps are still active, forming growth triangles. The age of initiation of growth and the total displacement of the oldest growth strata are known, permitting the determination of dip-slip rate. A requirement of this interpretation is that the ramps are not faulted, although some minor faulting is possible (Shaw and Suppe, 1996, p. 8626). The interpretation in Figure 2B is not unique; a ramp and backthrust are also consistent with the seismic data across the CLA fault (Shaw and Suppe, 1996, their Fig. 6).

The multichannel seismic lines do not provide information about the shallow two hundred meters of section, so these were provided by high-resolution seismic profiles calibrated by boreholes, which confirmed the location of the top of growth triangles. For the Puente Hills thrust, this confirmed evidence from the 1987 earthquake that the abrupt increments of growth accompanied earthquakes (Leon et al., 2007), but their presence at the top of the growth triangle for the CLA "trend" (Leon et al., 2009) was the first confirmation that the CLA structure also formed by successive earthquakes. Analysis of borehole stratigraphy across the top of growth triangles gave evidence for late Quaternary earthquakes on the underlying thrust ramps.

A



B



Two interpretations of the Compton-Los Alamitos thrust and Puente Hills thrust: A) from Wright (1991), where CLA thrust forms the foot of the Central Uplift of the Newport-Inglewood trend (Harding, 1973; Yeats, 1973; Yeats and Beall, 1991), here crossing the Potrero oil field. Solid triangles mark the total depth of wells, some of which cross the fault and permit testing of hypotheses of geometry of fault. B) From L. Leon and J.F. Dolan, in which the CLA overlies a north-dipping backthrust.

Figure 2	Existing structural models for the Puente Hills Thrust and Compton - Los Alamitos faults	Earth Consultants International ECI Proj No 3006 March 18, 2011

Observations

The high-quality 2D seismic data used by Shaw and Suppe (1996) permit the mapping of structure to depths of about 3 km. They correlated events in the dipping panels across growth-triangle boundaries with flat-lying strata, showing that the events were not faulted. However, the structure at greater depth could not be resolved using seismic data, although Shaw and Suppe (1996) assumed that the panels are unfaulted down to the speculated level of the thrust ramp. The American Petrofina wells were as deep as 21,250 feet (6,477 m) for the Central Core Hole, more than twice the depth of usable data from the seismic lines, permitting investigation of growth-triangle boundaries at deeper levels than those illuminated by seismic data.

We acquired data from electric logs, continuous 4-arm dipmeter logs, ditch-cutting logs, directional surveys, and well histories for all wells, and paleontology reports for all wells except for the American Petrofina wells, for which paleontology reports were not made available to us (not an industry confidentiality problem; the paleo reports simply cannot be found). The dipmeter logs provide information on changes in direction and amount of dip that reveal drag folding near faults and changes in attitude between footwall and hanging wall of a fault (Figure 4). This gives the information that strata at depth are faulted, with separations of hundreds of meters. Because the wells were more steeply inclined than bedding, we looked for and found evidence of repeated section on both sides of faults (Figures 3 and 4). We constructed structure contour maps of faults we mapped (Figure 5), which show the westward bend of the north end of the CLA fault, as mapped near the surface by Leon et al. (2009; their fig. 2). The contour marking the surface trace of the CLA fault as identified by high-resolution seismic profiles and boreholes at their Stanford Avenue traverse close to the Avalon Boulevard seismic line and the fold scarp farther west close to Florence Avenue, is parallel to the structure contour map of faulting at greater depths (Figure 5).

This is consistent with correlations across the CLA structure in the Avalon Boulevard and Vermont Avenue seismic profiles (Figures 6 and 7). Horizons in the shallower parts of these profiles are continuous across the CLA structure, as they are in the seismic profiles in Shaw and Suppe (1996), whereas faulting offsets the deeper horizons. The change

Pacific Electric Railway No. 1

The electric logs to the right show over 400' of repeated Repettian shale section in both the original (A, A') and redrill (B, B') wells. The repeated section indicates discrete faulting at a depth of 9000' bsl along the Compton-Los Alamitos fault zone.

Electric Logs

Electric logs show recorded spontaneous potential, resistivity and conductivity measurements of the stratigraphy at depth in the drill hole. The numbers in the middle represent measured depth, in feet, below the rotary table, and do not represent actual depth below sea leve due to the inclination of the well holes. As such, thicknesses of defined units on the logs do not represent true vertical thicknesses. All thicknesses and depths reported in this figure have been corrected to true vertical thickness in feet, and feet below sea level. Red lines indicate faults, black lines demarcate repeated sections on the log and arrows point upsection.

La Tijera EH-1A (RD)

The electric logs to the right show multiple faults juxtaposing a thrice-repeated 300' thick section (C, C', C") of Repettian shale and siltstones in the well. The repeated sections indicate discrete faulting at a depth of 6500' bsl along the Puente Hills fault zone.

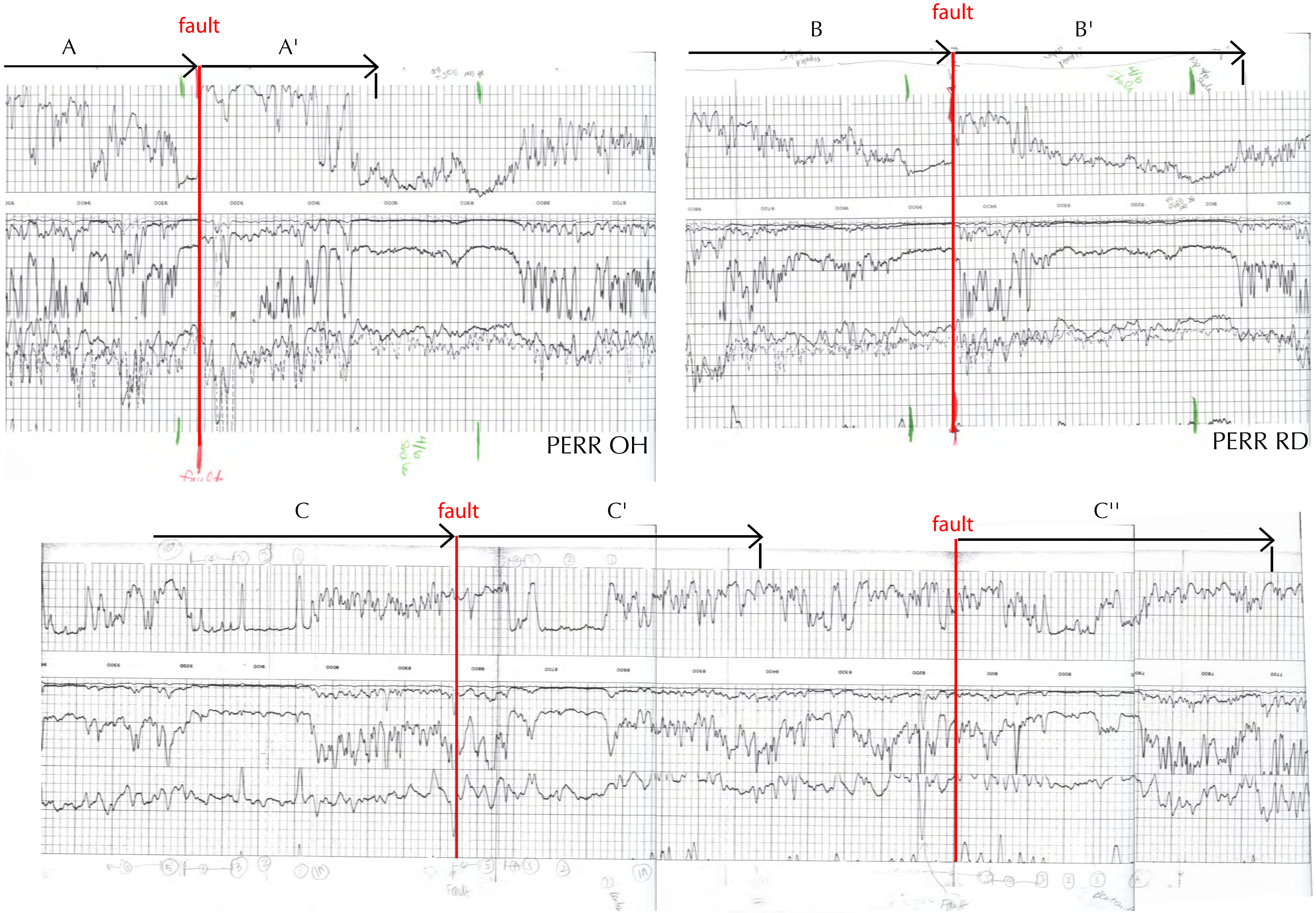


Figure 3

Portions of electric logs showing repeated stratigraphic sections at depth on the Puente Hills and Compton-Los Alamitos faults

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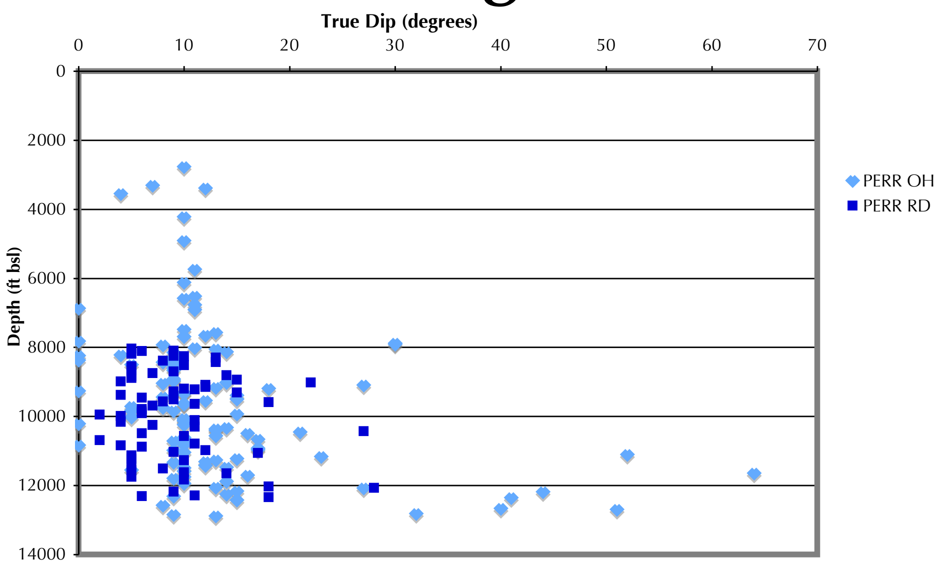
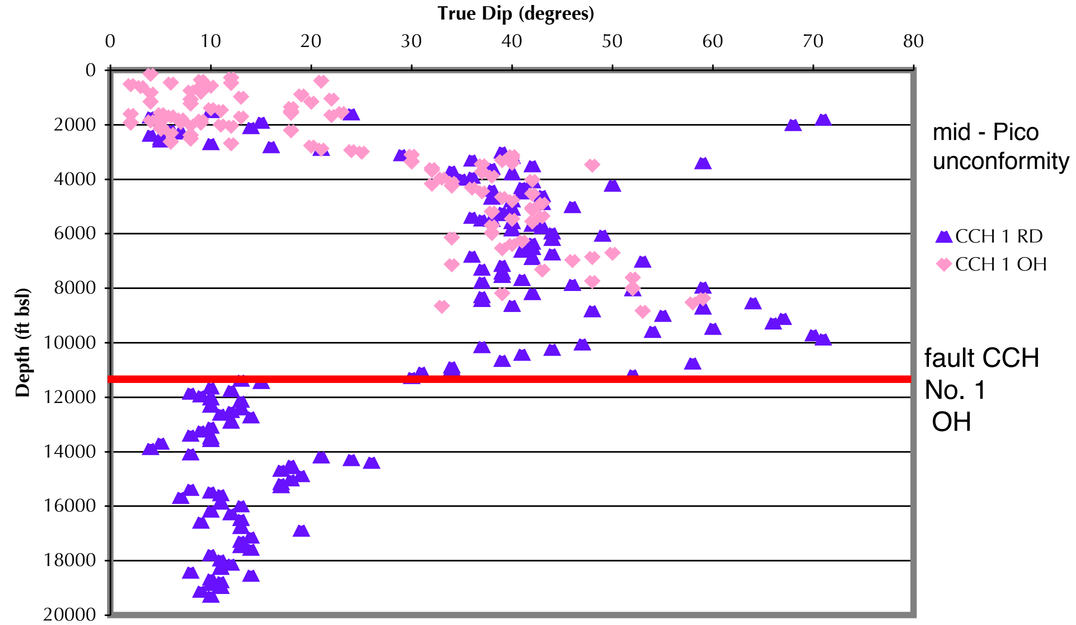
Wells Crossing CLA fault



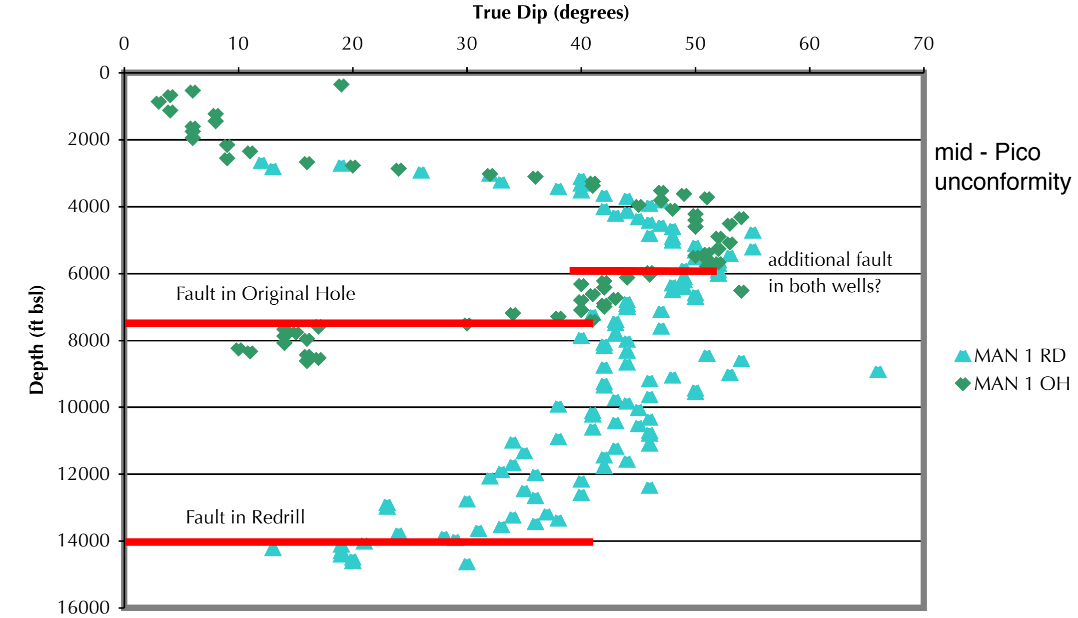
Pacific Electric Railroad

The dipmeter data for the PERR well is sparse and unfortunately does not show the repeated faulted section at 9000' bsl that is obvious in the e-logs. The wider variation in dip data is because the average dip of the units is around 10 degrees, low enough that the 4-armed dipmeter loses some precision by potentially double-picking contacts, etc.



American Petrofina Central Core Hole No. 1

Two things are notable on this plot. One, the abrupt 30-degree change in average dips below 11000' marks the discontinuity between folded Pico and Repetto Formations in the hanging wall to undeformed Repetto units in the footwall. Also note that at a depth of 3000', there is a gradual increase in average dip likely due to the mid-Pico unconformity, an angular unconformity identified across the basin created by erosion of pre-mid-Pico depositional units. This unconformity is present at roughly the same elevation in the Manchester well along the CLA (see plot to the right), as well as in the hanging wall of the PHT at 4500' bsl (see plot below and left). Finally, there is no expression of the CLA in the original hole (OH) because the well was not drilled deep enough to reach the footwall block.



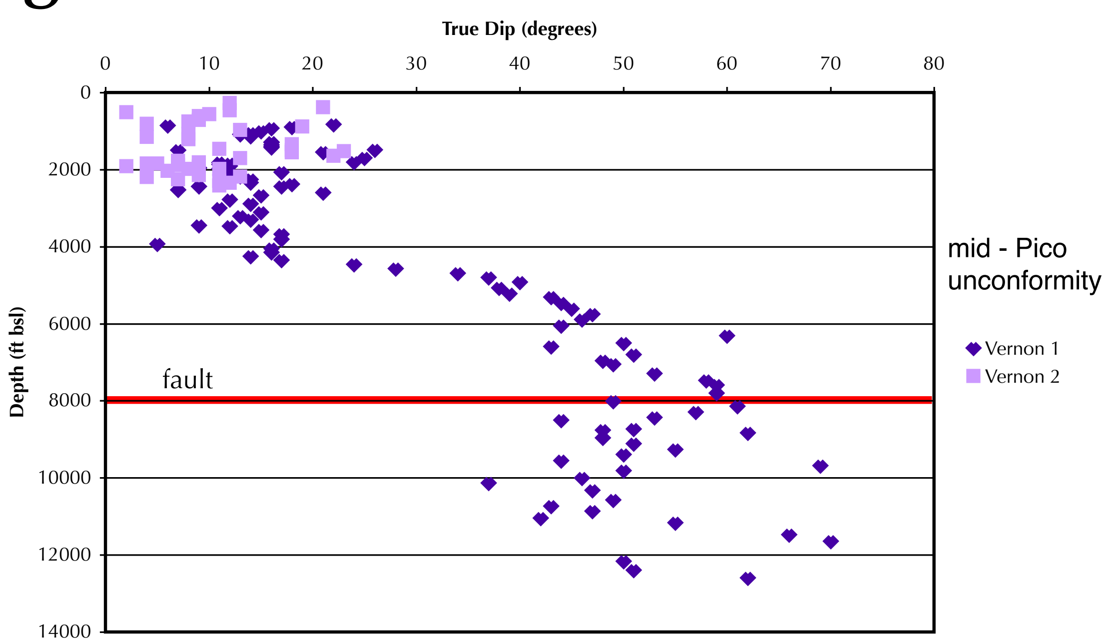
American Petrofina Manchester No. 1

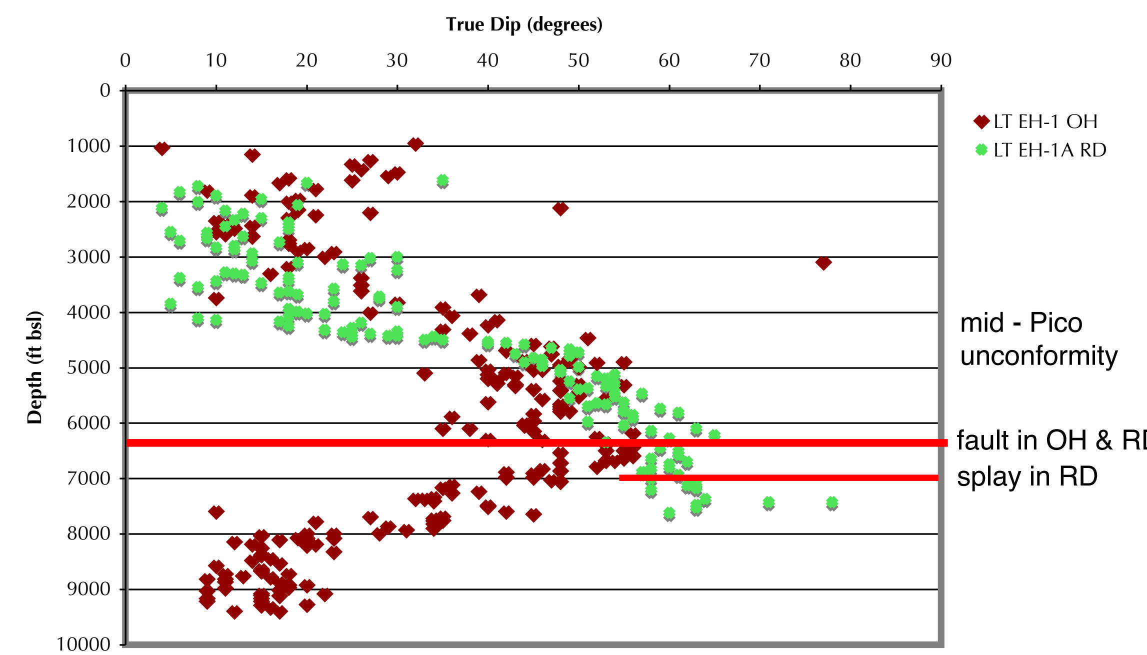
The Manchester well crosses the fault in both the original hole (OH) and the redrill (RD), like the PERR well. The fault juxtaposes 40-degree hanging wall dips above 15-degree footwall dips at 7500' depth in the OH, and at 14000' in the RD. The mid-Pico unconformity is also present in both wells at a depth of 3000'. There is also the potential for another structure around 6000' that won't be resolved until we acquire the paleo data.

Wells Crossing PHT fault

American Petrofina Vernon No. 1 and 2 (right)

The mid-Pico unconformity occurs at the same depth as in the La Tijera original hole (OH) and redrill (RD). The fault in Vernon No. 1 occurs at 8000', where gradually increasing dips begin to fan out. The Vernon No. 2 well does not extend deep enough through the hanging wall to cross the fault.





Union-Standard La Tijera EH (left)

The mid-Pico unconformity occurs in both the OH and RD in the La Tijera well at 4500' bsl. The fault (and its splays) occur between 6400'-7000' bsl, evidenced also by repeated section in the e-log for the RD.

Figure 4

Dipmeter data plotted as a function of depth illustrating unconformities and fault zones in wells crossing the the Puente Hills and Compton-Los Alamitos faults

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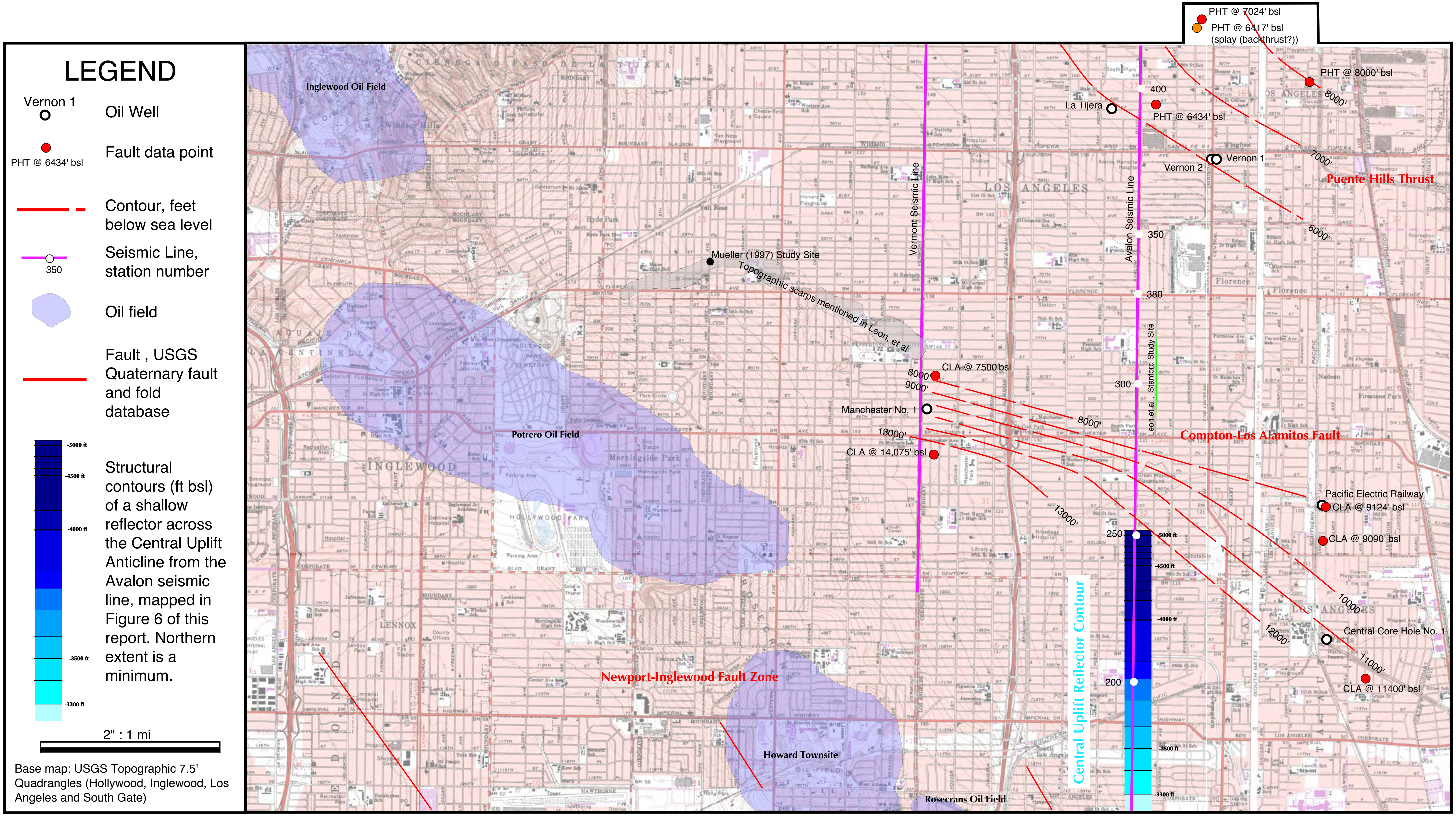

Figure 5

Contour map of the Puente Hills and Compton - Los Alamitos faults and the Central Uplift Anticline

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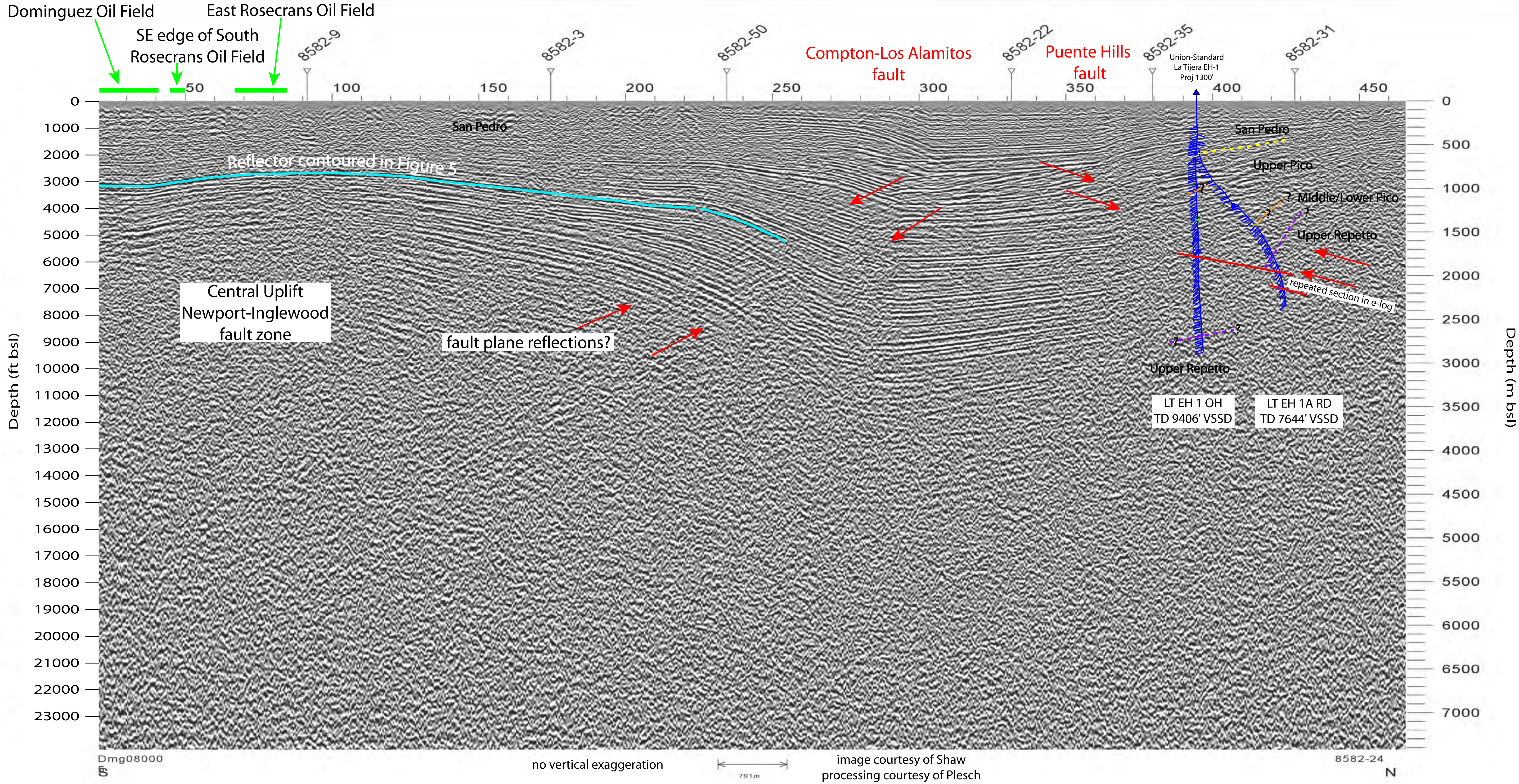

Figure 6

Annotated Avalon Seismic Line
with Central Uplift Reflector and La Tijera Oil Well and Dip Data

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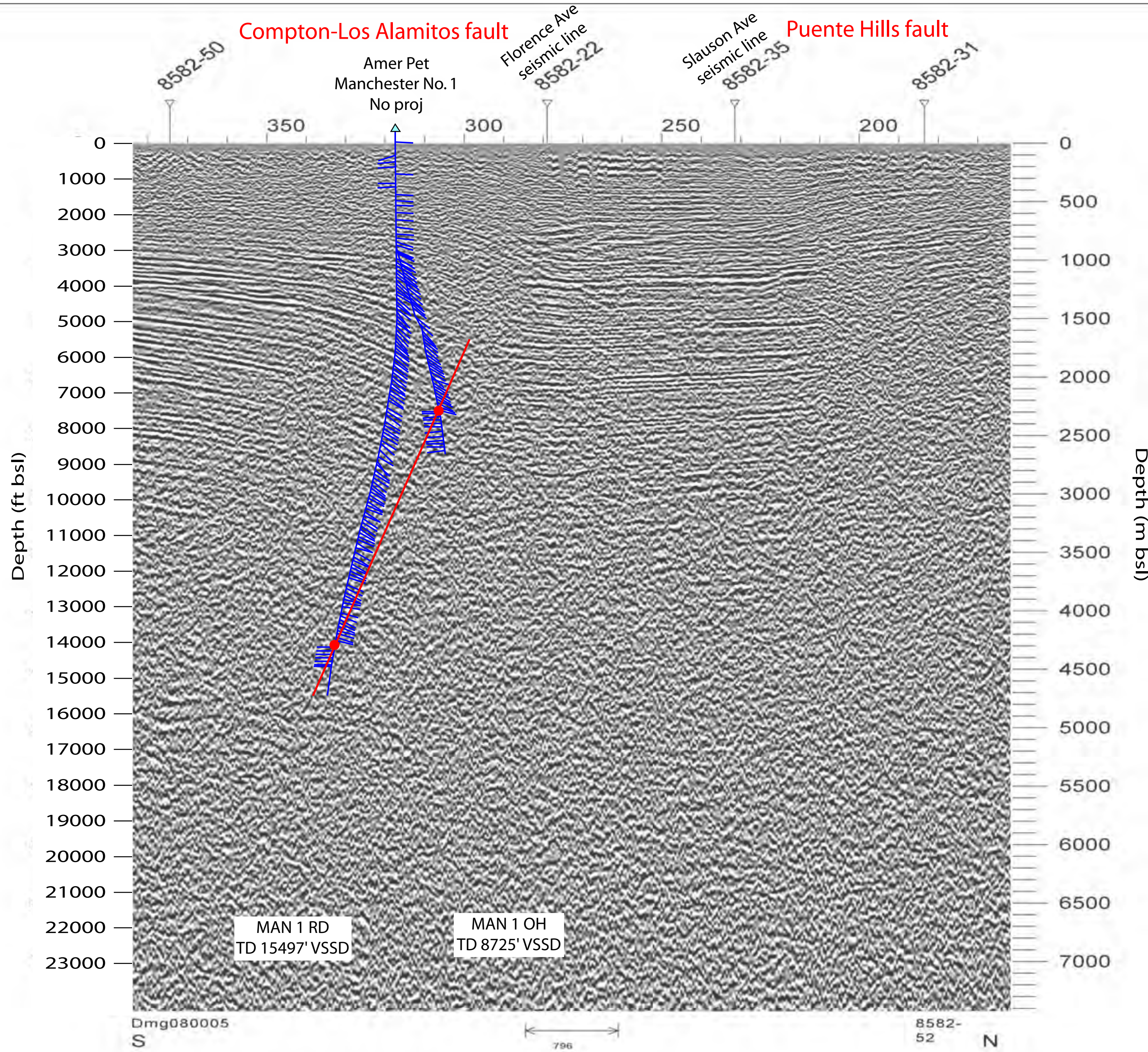

Figure 7

Annotated Vermont Seismic Line
with Manchester well and dip data

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from continuous to faulted horizons takes place down-section in the Avalon profile and in the Vermont profile. These relations indicate that the CLA is a fault-propagation rather than a fault-bend fold structure**.**

The dipmeter shows an abrupt change at the CLA fault from moderately-dipping NE in the hanging wall to nearly flat-lying in the footwall (Figure 7). The seismic profiles show that the strata between the CLA and Puente Hills faults are nearly flat-lying rather than forming a broad syncline, as shown by Wright (1991) (Figure 2A). The strata dip gently south, although close to the CLA fault, strata dip gently north. The Avalon Boulevard profile extends southward across a broad anticline that includes the Newport-Inglewood fault zone (NIFZ; Figure 6). This broad anticline is shown in Wright (1991, his figure 8c; Figure 2A) as extending across the Potrero oil field, with the Potrero right-lateral fault at the crest of the structure and southwest dips farther southwest. We call this the Central Uplift anticline (Figures 5 and 6), following usage among some operators in oil fields along the NIFZ. This broad anticline is shown in structure contour maps by Harding (1973, his figure 1), McMurdie (1973, his plate 1), and Wright (1991, his figure 9) and our figure 5. These structure contour maps show the broad NE-dipping flank of this anticline, with the CLA fault at its base, and a narrow SW dipping flank immediately southwest of and close to the NIFZ. The CLA fault intersects the NIFZ between the Potrero and Inglewood oil fields, as shown by Leon et al. (2009, their Figure 2) and in our Figure 5.

This leads to an alternate interpretation of the CLA fault as a reverse fault related to the NIFZ, analogous to reverse faults in the Dominguez oil field (McMurdie, 1973; Yeats, 1973), the Potrero and Rosecrans oil fields to the north, and the deep Sentous thrust in the Inglewood oil field (Wright, 1991; Elliott et al., 2009), but larger. We speculate that these reverse faults are capable of producing reverse-fault earthquakes in their own right, analogous to the Coalinga and Kettleman Hills reverse-fault earthquakes in the central Coast Range and the reverse-fault aftershock series on the Enriquillo fault following the 12 January 2010 earthquake in Haiti, both illustrating strain partitioning in a largely strike-slip fault system. The Baldwin, Rosecrans, and Dominguez Hills in the northern NIFZ were not uplifted due to pure strike slip, although Yeats (1973) had emphasized that the orientation of reverse faults at Dominguez and nearby oil fields is due to basement anisotropy rather than a regional pattern related to the Central Uplift anticline. The 1933 earthquake on the NIFZ was accompanied by regional uplift on the CLA fault northeast of the Long Beach and Seal Beach anticlines, with a maximum uplift of 0.610 feet and width of about 4 miles parallel to the NIFZ (Gilluly and Grant, 1949; Barrows, 1974).

Hauksson (1987) analyzed 64 earthquakes along the NIFZ recorded during 1973 to 1985 with $M_l \geq 2.5$, obtaining fault-plane solutions for 39 earthquakes. He divided the NIFZ into a section from Dominguez Hills southward that yield predominantly strike-slip fault-plane solutions with some normal-fault solutions, and a northern area with reverse-fault solutions as well as strike slip. The southern band of earthquakes was concentrated in a band 4 to 5 km east of the NIFZ, the location of his Alamitos fault (the southern part of the CLA fault). In the northern section, the earthquakes are located in the vicinity of the NIFZ and the maximum principal stress is N 10°-25° E. These results are consistent with a strain-partitioning interpretation of the CLA fault.

Conclusions

Analysis of wells drilled as part of the American Petrofina exploration of the deep LA Basin includes data from as deep as 6.4 km, twice the depth of usable data from multichannel seismic lines. Data analyzed include electric logs, dipmeter, ditch-cutting logs, and directional surveys for all wells plus paleontological data from all wells except the American Petrofina Exploration Co. boreholes. These wells show evidence of reverse faulting at depth, whereas shallower data indicate folding rather than faulting, with development of growth triangles. We interpret the CLA and Puente Hills structures as fault-propagation folds rather than fault-bend folds. The CLA reverse fault east of the NIFZ suggests that some earthquakes develop due to strain partitioning, an interpretation supported by seismicity data as well as evidence for uplift accompanying the 1933 earthquake near the CLA fault east of the Long Beach and Seal Beach oil fields. This leads to a modification of seismic hazard to include reverse faulting on the CLA as part of the NIFZ fault system as well as on the Los Angeles segment of the Puente Hills reverse fault.

References

Barrows, A.G., 1974, A review of the geology and earthquake history of the Newport-Inglewood structural Zone, southern California: *Calif. Div. Mines and Geology Special Report 114*, 115 p.

Davis, T.L., Namson, J., and Yerkes, R.F., 1989, A cross section of the Los Angeles area: Seismically active fold and thrust belt, the 1987 Whittier Narrows earthquake, and earthquake hazard: *Jour Geophys. Research 94*:9644-9664.

Elliott, J.P., Lockman, D., and Canady, W., 2009, Multiple uses for image logs within the Los Angeles basin: Society of Petrophysicists and Well Log Analysts (SPWLA) 50th Annual Logging Symposium, Woodlands, TX, June 21-24, 2009, 16 p.

Gilluly, J., and Grant, U.S., 1949, Subsidence in the Long Beach harbor area, California: *Geol. Soc. America Bull. 60*:461-529.

Harding, T.P., 1973, Newport-Inglewood trend, California—An example of wrenching style of deformation: *AAPG Bull. 57*:97-116.

Hauksson, E., 1987, Seismotectonics of the Newport-Inglewood fault zone in the Los Angeles Basin, California: *Seismol. Soc. America Bull. 77*:539-561.

Hauksson, E., Jones, L.M., Davis, T.L., Hutton, K., Brady, A.G., Reasenberg, P.A., Michael, A.J., Yerkes, R.F., Williams, P., Reagor, G., Stover, C.W., Bent, A.L., Shakal, A.K., Etheredge, E., Porcella, R.L., Bufe, C.G., Johnston, M.J.S., and Cranswick, E., 1988. The 1987 Whittier Narrows earthquake in the Los Angeles metropolitan area, California: *Science 239*:1409-1412.

Leon, L.A., Christofferson, S.A., Dolan, J.F., Shaw, J.H., and Pratt, T.L., 2007, Earthquake-by-earthquake fold growth above the Puente Hills blind thrust fault, Los Angeles, California: Implications for fold kinematics and seismic hazard: *Jour. Geophys. Research 112*, B03S03,doi:10.1029/2006JB004461.

Leon, L.A., Dolan, J.F., Shaw, J.H., and Pratt, T.L., 2009, Evidence for large Holocene earthquakes on the Compton thrust fault, Los Angeles, California: *Jour. Geophys. Research 114*, B12305, doi:10.1029/2008JB006129.

Lin, J., and Stein, R.S., 1989, Coseismic folding, earthquake recurrence, and the 1987 source mechanics at Whittier Narrows, Los Angeles Basin, California: *Jour. Geophys. Research 94*:9614-9632.

McMurdie, D.S., 1973, The geology and general history of the Dominguez oil field in an urban environment, Los Angeles County, California, *in* Metropolitan oil fields and their environmental impact: AAPG Trip 1, 1973 Annual Meeting AAPG-SEPM-SEG, Plate 1, compiled by D.S. McMurdie, J.C. Taylor, and J.N. Truex.

Myers, D.J., Nabelek, J.L., and Yeats, R.S., 2003, Dislocation modeling of blind thrusts in the eastern Los Angeles basin, California: *Jour. Geophys. Research 108*(9):doi:10.1029/2002JB002150.

Schneider, C.L., Hummon, C., Yeats, R.S., and Huftile, G.J., 1996, Structural evolution of the northern Los Angeles Basin, California, based on growth strata: *Tectonics 15*:341-355.

Shaw, J.H., and Suppe, J., 1996, Earthquake hazards of active blind-thrust faults under the central Los Angeles basin, California: *Jour. Geophys. Research 101*:8623-8642.

Shaw, J.H., and Shearer, P. M., 1999, An elusive blind-thrust fault beneath metropolitan Los Angeles: *Science 283*:1516-1518.

Shaw, J.H., Plesch, A., Dolan, J.F., Pratt, T.L., and Fiore, P., 2002, Puente Hills blind-thrust system, Los Angeles, California: *Seismol. Soc. America Bull. 92*:2946-2960.

Shearer, P.M., 1997, Improving local earthquake locations using the L1 norm and waveform cross correlation: Application to the Whittier Narrows, California, aftershock sequence: *Jour. Geophys. Research 102*:8269-8283.

Stein, R.S., and Yeats, R.S., 1989, Hidden earthquakes: *Scientific American 260*(6):48-57.

Suppe, J., 1983, Geometry and kinematics of fault-bend folding: *Amer. Jour. Science 283*:684-721.

Tsutsumi, H., Yeats, R.S., and Huftile, G.J., 2001, Late Cenozoic tectonics of the northern Los Angeles fault system, California: *Geol. Soc. America Bull. 113*:454-468.

Wright, T.L., 1991, Structural geology and tectonic evolution of the Los Angeles Basin, in Biddle, K.T., ed., *Active Margin Basins: AAPG Mem. 52*:35-134.

Yeats, R.S., 1973, Newport-Inglewood fault zone, Los Angeles Basin, California: *AAPG Bull. 57*:117-135.