

1. NEOGENE TECTONICS OF SOUTHERN CALIFORNIA.

The focus of this research project is to investigate the timing of rotation of the Transverse Ranges and the evolution of the 3-D architecture of the Los Angeles basin. Objectives are to understand better the seismicity of the region and the relationships between petroleum accumulations and the structure and stratigraphic evolution of the basin. Figure 1 shows the main physiographic and structural features of the Los Angeles basin region, the epicenter of recent significant earthquakes and the our initial study area in the northeastern Los Angeles basin.

Los Angeles basin tectonic model:

Most tectonic models attribute the opening of the Los Angeles basin to lithospheric extension produced by breakaway of the Western Transverse Ranges from the Peninsular Ranges and 90 degrees or more of clockwise rotation from ca. 18 Ma to the present. Evidence of this extension includes crustal thinning on tomographic profiles between the Santa Ana Mountains and the Santa Monica Mountains and the presence in the Los Angeles basin of Middle Miocene volcanic rocks and proto-normal faults. Detailed evidence of the 3-D architecture of the rift created by the breakaway and the timing of the rift phase has remained elusive.

The closing of the Los Angeles basin in response to N-S contraction began at ca. 8 Ma and continues today (Bjorklund, et al., 2002). A system of active faults has developed that pose significant seismic hazards for the greater Los Angeles region. Crustal heterogeneities that developed during the extension phase of basin development may have strongly influenced the location of these faults. Uncertainties in fault location geometries and in how movement on one fault may affect movement on other faults have not yet been well quantified. We plan to carry out regionally integrated analyses of geophysical and geologic data that we hope will lead to improved 3-D models of the Los Angeles basin and better definition of the seismic hazards.

Whittier fault model:

Whittier fault is a high-angle reverse fault, which trends N70°W along a 40 km strike-length, which is part of the San Andreas fault system and the subject of our initial study in the northeastern Los Angeles basin (Bjorklund and Burke, 2002). Figure 2 is a cross section located in the central part of the Whittier fault trend. Along the central part of the structure, strata in the hanging wall block form a broad anticline and strata in the footwall block dip steeply south on the north limb of an asymmetric syncline. The maximum vertical separation due to folding and offset along the Whittier fault is more than 4 km. Analysis of surface geologic maps and data from hundreds of oil wells and the application of balanced cross section techniques reveal a three-phase evolution of the Whittier fault that we have represented graphically in Figure 3. The three phases consist of the following.

- Rotation of the Western Transverse Ranges block and the formation of the proto-Whittier normal fault and associated half-graben (ca. 14-10 Ma). During that time, organic-rich shale (oil source rock) was deposited in the half-graben and throughout the Los Angeles basin.
- Transpression along the San Andreas fault and reactivation of the proto-Whittier fault as a basement-involved reverse fault (ca. 8 Ma). Over the next 8 million years, structural uplift continued and turbidite fan-channel systems and pelagic sediments eventually filled the Los Angeles basin. Beginning at ca. 3 Ma, oil generated from the organic-rich shale accumulated in structures along the Whittier fault, which became the oil fields that exist there today.
- Breakthrough onto the seafloor of the reactivated proto-Whittier fault and formation of the present throughgoing Whittier fault system (ca. 0.5 Ma). Continued uplift led to subaerial exposure of the hanging wall block.

Over 600 MMBO have been produced from structural and stratigraphic traps along the Whittier fault and about 35 MMBO remain to be produced. Oil accumulations range in depth from less than 200 meters to 2400 meters and include simple structural closures, faulted noses, combination structural and stratigraphic traps and purely stratigraphic traps, one of which is a large accumulation in the footwall syncline of the inverted Whittier fault structure (Yorba Linda field). During the period of structural inversion on the Whittier fault, an oil accumulation, which would have become the largest oil field in the Los Angeles basin, may have formed in the Soquel sandstone on the crest of the inverted structure. Recoverable oil could have exceeded 3 billion barrels. If the accumulation existed, it has since been uplifted and completely eroded, leaving to be produced today small, fractured reservoirs on the crest of the exhumed structure and downdip accumulations on the flanks of the structure.

Hydrocarbon accumulations associated with inversion structures like the Whittier fault may lie buried in the undrilled deeper parts of the Los Angeles basin. Such structures may not have experienced the complete cycle of deformation exhibited by the Whittier fault and may now exist as simple half grabens or as inverted half grabens with folded but unfaulted sedimentary strata. The first possibility could juxtapose Miocene source rocks and Paleogene and Cretaceous sandstones that thus far have been unproductive and largely undrilled in the Los Angeles basin. The second possibility could result in large, low relief structures with the potential for significant hydrocarbon accumulations that might be difficult to recognize on vintage seismic data.

Future Research:

Our future research in the Los Angeles basin will expand the studies begun in the northeastern Los Angeles basin to the entire basin. The studies will investigate the merits of applying the Whittier fault model to other important faults in the basin to understand better the seismicity and structural evolution of the basin. We also hope that the results of the studies will allow us to quantify the remaining potential for significant

undiscovered hydrocarbon accumulations in the basin. The cross sections in Figure 4 are representative of cross sections that we plan to construct throughout the Los Angeles basin area (Bjorklund, et al., 2002).

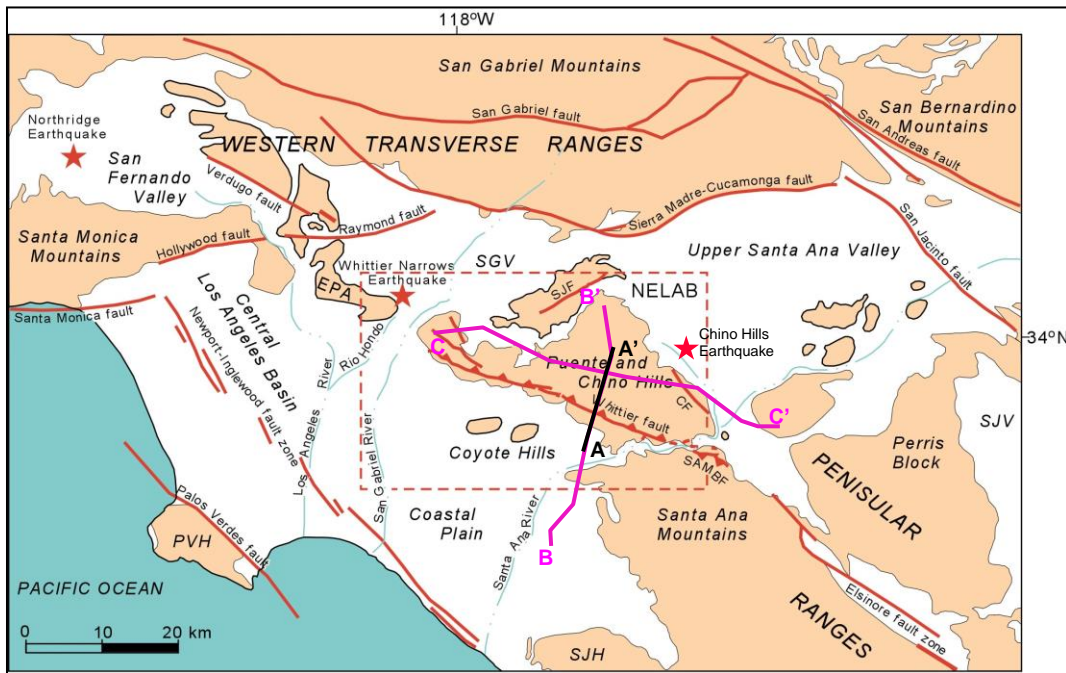


Figure 1. Index map of the Los Angeles basin region. The red-dashed rectangle in the center of the map locates the Whittier fault and our northeastern Los Angeles basin study area. Lines A-A', B-B' and C-C' are the locations of cross sections in Figures 2, 3 and 4. The red stars are the epicenters of important recent earthquakes in the area.

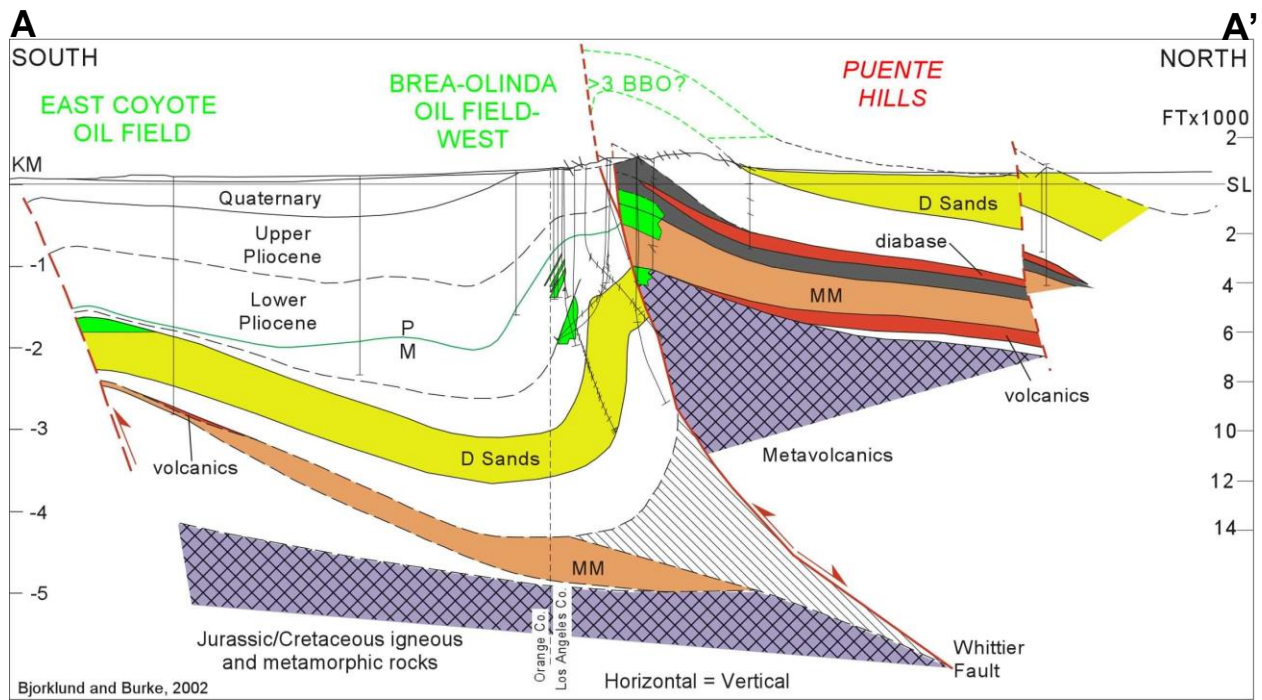


Figure 2. Miocene turbidite fan-channel sandstones are productive in the footwall block of the Whittier fault on the steeply-dipping south flank of the Puente Hills anticline. Stratigraphically controlled oil accumulations in Pliocene rocks are present in the footwall syncline east and west of the cross section. Over 3 MMBO have been produced since 1880 from fractured Upper Miocene La Vida shale, Middle Miocene Topanga sandstone and Jurassic basement rocks on the crest of the Puente Hills anticline.

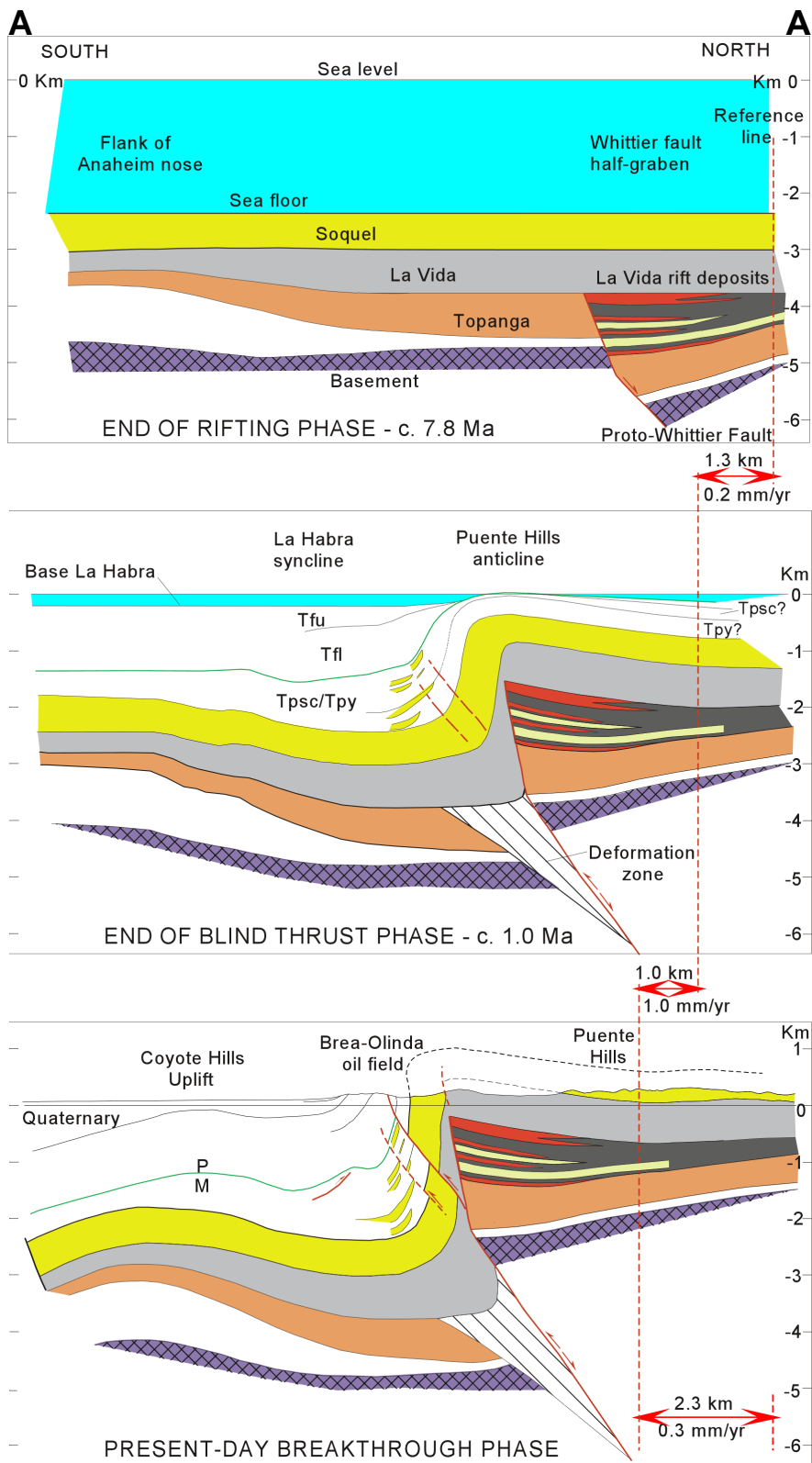


Figure 3. Retrodeformation of cross section in Figure 2 showing three-phase evolution of the Whittier fault. The cross section is balanced, based on our interpretation of a N-S tectonic transport direction and using the balancing method proposed by Cook (1988) for basement-involved structures. A. Rift Phase: 14-8 Ma. B. Blind Reverse Fault Phase: 8-0.5 Ma. C. Fault Breakthrough Phase: 0.5 Ma-Present. Yorba member (Tpy), Sycamore Canyon member (Tpsc), Miocene (M), Pliocene (P), Lower Fernando member (Tfl) and Upper Fernando member (Tfu).

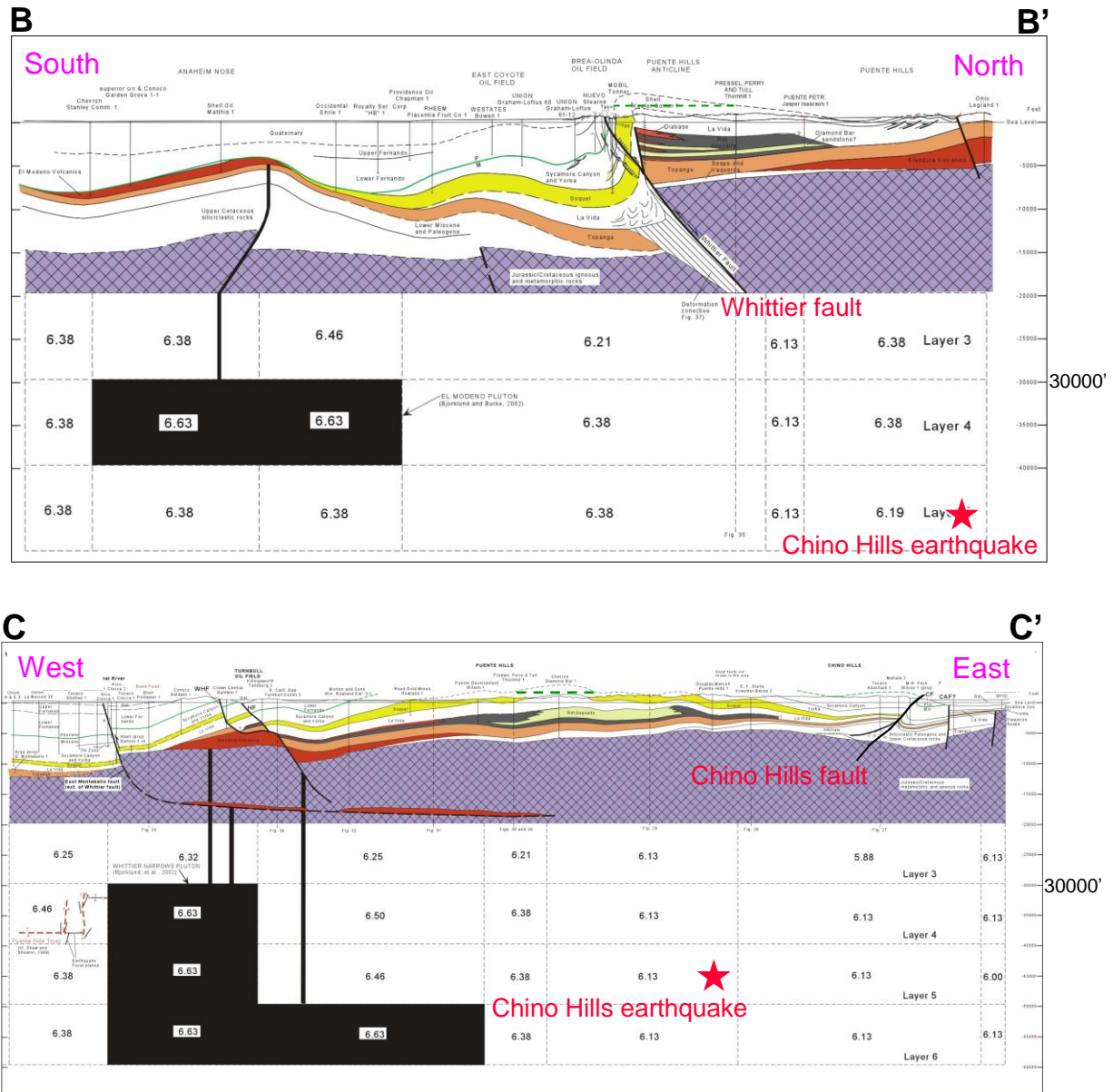


Figure 4. Cross sections B-B' and C-C' combine well and outcrop data and tomographic velocities to show spatial relationships of volcanic rocks (red) and inferred, Miocene plutons (black) that are the possible sources of volcanic sills and flows (red). Dashed rectangles are velocity model grid blocks with average P-wave velocities (km/s) from Hua-wei Zhou's Southern California velocity model. We interpret the higher-velocity anomalies to indicate a vertical, stock-like pluton (cross section C-C') and a tabular, sill-like pluton (cross section B-B') that we have named the Whittier Narrows and El Modeno plutons, respectively. We suggest that both plutons were emplaced into the upper crust during the Miocene and were the magma sources for the overlying volcanic rocks. We projected the hypocenter of the recent Chino Hills earthquake (July 29, 2008) (location from Hauksson, et al.) to the cross sections at the depth of the earthquake. The location of the Whittier fault on cross section C-C' is much shallower than the depth of the projected hypocenter because the fault dips 60 degrees to the north and the hypocenter is located north of the cross section line. The western part of the section is parallel to the strike of the Whittier fault. The Chino Hills earthquake and its aftershocks (not shown) do not appear to relate simply to a single known fault, although the focal mechanism of the initial event is consistent with our interpretation of the geometry and kinematics of the Whittier fault..