AN ABSTRACT OF THE THESIS OF

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Title: Subsurface Structural Evolution along the Northern Whittier Fault Zone of the Eastern Los Angeles Basin, Southern California

Abstract approved: [redacted]
Robert S. Yeats

The Whittier fault forms the central part of a fault system extending from the East Montebello fault at Whittier Narrows to the Elsinore fault, which is traced as far as the Mexican border. The Whittier fault forms a restraining bend in this fault system, resulting in uplift of the Puente Hills. The northwestern part of the Whittier fault in the Whittier oil field in the eastern Los Angeles basin strikes approximately N65°W and dips 70-75° northeast. The fault is near the range front of the Puente Hills northwest of Turnbull Canyon, and within the Puente Hills to the southeast.

The central reach of the Whittier fault had normal separation in the Relizian and Luisian stages of the middle Miocene. From the Mohnian through Repettian stages of the late Miocene and early Pliocene, little, if any, offset occurred until the initiation of reverse offset in the Venturian stage of the late Pliocene. A component of right-lateral strike-slip may have been added near the end of the Pliocene, coinciding with the formation of the Elsinore fault. The Workman Hill and Whittier Heights faults may have formed in the late Pliocene to early Pleistocene, coinciding with the possible initiation of strike-slip on the Whittier fault. The present sense of slip on the Whittier fault southeast of the study area is nearly pure right-lateral strike-slip, with a slip rate of 2-3 mm/yr. The northwestern part of the Whittier fault has a component of reverse slip of approximately 1 mm/yr. The amount of strike-slip on this part of the fault was not determined by this study.

The Rideout Heights, 304, and 184 low-amplitude anticlines formed in the Whittier oil field area in the late Miocene and early Pliocene. The

Rideout Heights anticline is a southwest-verging fault-propagation fold trending northwesterly from the mouth of Turnbull Canyon through the Rideout Heights area. Strata are overturned in the southwest limb of the fold, and normally dipping in the northeast limb; the fold has been cut along its hinge by the Whittier fault.

The 304 and 184 anticlines are north-verging and appear to be bedding-plane shear folds in the northeast limb of the La Habra syncline. Recent strike-slip on the Whittier fault may have reactivated the 184 anticline, causing uplift of the footwall block south of Turnbull Canyon. North of Turnbull Canyon, the Whittier fault is at the range front with no evidence of Quaternary footwall uplift. The 304 anticline could be a fault-propagation fold from a previously-unknown southwest dipping blind reverse fault south of the Whittier fault; uplift on this fold could also be the cause of footwall uplift south of Turnbull Canyon.

Active fault traces, possibly strike-slip, are on or near the Whittier fault south of Turnbull Canyon, but to the north, recent offsets appear to be northeast of the Whittier fault in the Puente Hills. These offsets may represent an attempt of the Whittier fault to straighten itself by bypassing the restraining bend at Turnbull Canyon. If so, this movement is too recent to offset conglomerate beds more than a few tens of meters.

Subsurface Structural Evolution along the Northern Whittier Fault Zone of the Eastern Los Angeles Basin, Southern California

by

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[redacted]

Chair of Department of Geosciences

[redacted]

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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David W. Herzog, Author

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Most importantly, I would like to thank my wife Cynthia, whose support and encouragement provided me the opportunity to successfully complete this project.

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INTRODUCTION

Purpose

The purpose of this study is to define the subsurface structural geology and structural evolution along the northwestern segment of the Whittier fault in the Whittier oil field area of the northeastern Los Angeles basin (Figure 1). The principal source of information for this study is oil well data sets: including lithology, dipmeter, biostratigraphy, and electric logs. Other sources of information include geologic maps by Yerkes (1972), Cross (1948), and Daviess and Woodford (1949), and a proprietary oil-company report on the central area of the Whittier oil field. The work of Wright (1991) and Yeats and Beall (1991) were also invaluable sources of information.

The Whittier oil field is located at the western end of the northwest trending Whittier fault, which is part of the Elsinore-Whittier-East Montebello fault system, a major structural feature in southern California extending north from the Mexican border to the Whittier Narrows of the San Gabriel Valley (Figure 1).

The Whittier fault is considered a seismic hazard in the Los Angeles basin, even though no major historic earthquakes have occurred on this fault (Gath et al., 1992). The recurrence interval for a magnitude 7 earthquake on the Whittier fault is 700-1000 years, but even though the last known offset on the fault occurred at least 1400 years ago, the Working Group on California Earthquake Probabilities (1995) assigns only a 5% probability that the fault will rupture before the year 2024 (Patterson and Rockwell, 1993). If the recurrence

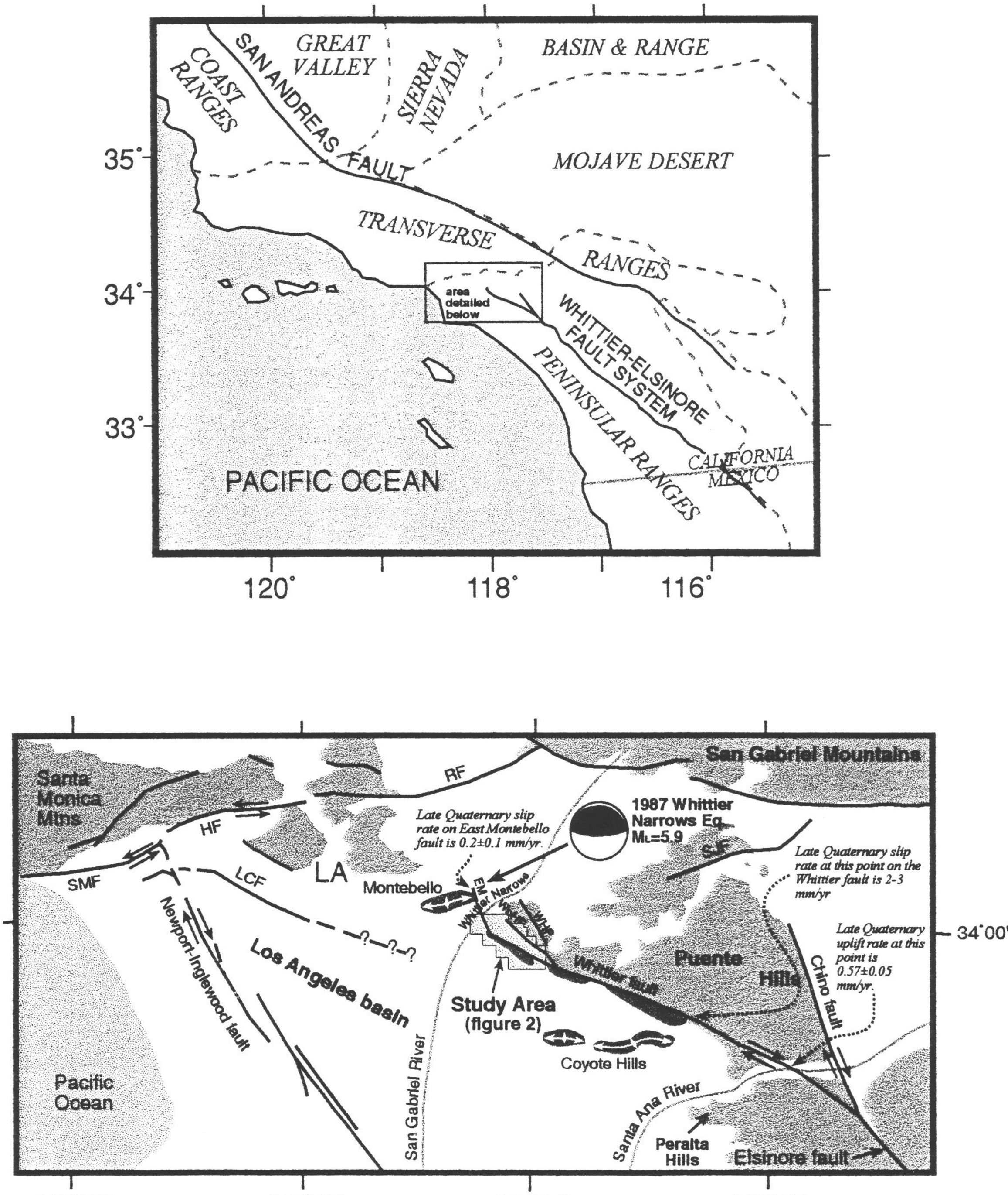


Figure 1 Maps showing features presented in the text, along with other prominent features for reference. Key to abbreviations: EM-East Montebello fault; HF-Hollywood fault; LA-downtown Los Angeles; LCF- Las Cienegas fault; RF-Raymond fault; SJF- San Jose fault; SMF-Santa Monica fault; WHF-Whittier Heights fault; WoHF-Workman Hill fault. Lighter shading indicates highlands. Darker shading indicates selected oil fields (after Wright, 1991).

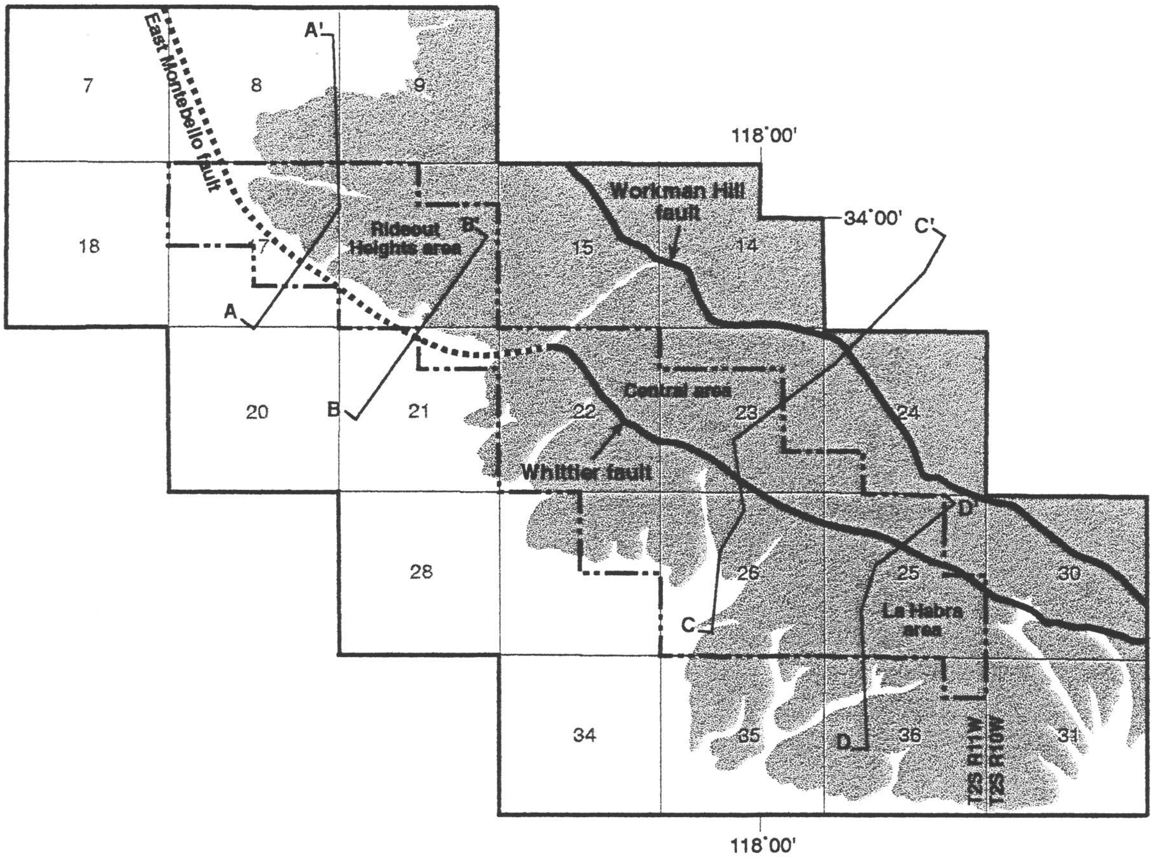


Figure 2 Study area map. Shading indicates the Puente Hills. Dashed and dotted line shows the border of the Whittier oil field based on well map information from the California Department of Oil and Gas, with the Rideout Heights, Central, and La Habra areas labeled on the map. Solid fault lines indicate where the major faults are present at the surface, and dotted where projected to the surface through overlying alluvium.

interval is correct, then there should be a higher probability that the fault will rupture before that time. The possibility exists that the actual recurrence interval may be longer; more work needs to be done to better characterize the Whittier fault.

Previous work

This section reviews the work of other investigators on the history of the Whittier fault, mainly along the southeastern segment of the fault. The initial apparent motion on the Whittier fault zone was dip-slip, with the northeast side moving down in the middle to late Miocene (middle to upper Mohnian). Middle to late Miocene strata northeast of the Whittier fault thicken toward the fault, while the same strata are thinner southwest of the fault (Yeats and Beall, 1991). The timing of the Whittier fault's development in late Miocene is supported by a late Miocene diabase that is injected into the fault zone (Durham and Yerkes, 1964). Based on the current orientation of the fault and on its steep dip to the northeast, it would have been a normal fault at that time, which corresponds with regional extension that was occurring in the Miocene (Campbell and Yerkes, 1976; Yeats, 1976; Wright, 1991; Schneider et al., 1996).

During the late Miocene through the Pliocene, coinciding with the formation of the northwest-trending Los Angeles trough, motion on the central and southeastern segments of the fault was apparently southwest side down, a switch to reverse separation caused by a change to regional contraction and uplift of the area north of the Whittier fault (Wright, 1991; Yeats and Beall, 1991). Evidence for this is the presence of late Miocene-Pliocene growth strata south of the Whittier fault. Sandstone beds in

Pliocene strata thin and pinch out northward toward the fault, and stratigraphic separation along the Whittier fault shows apparent south-side down separation from 600-900 meters at the north and south ends of the fault, to nearly 4300 meters near the middle of the fault (Davis et al., 1989; Wright, 1991).

Near the end of the Pliocene, around 2.5 Ma, motion on the Whittier fault changed to right-lateral strike-slip, coinciding with the formation of the right-lateral strike-slip Elsinore fault to the south, which may have resulted from a change in the local principal compressive stress orientation to a more north-south orientation (Lamar, 1992; Hull and Nicholson, 1992; Magistrale and Rockwell, 1996). The present sense of slip near the southeastern end of the Whittier fault is almost pure strike-slip (Rockwell et al, 1988; Patterson and Rockwell, 1993). The late Quaternary slip-rate on the Whittier fault at Olinda Creek is 2-3 mm/yr (Figure 1; Gath et al., 1995). Movement on the Whittier fault is due to the partial transfer of 5-6 mm/yr of slip from the northernmost segment of the Elsinore fault (Gath et al., 1992; Hull and Nicholson, 1992). The remaining slip from the Elsinore fault is probably taken up by bedding plane deformation and folding in the Puente Hills, by slip on the Chino fault, and by anticlinal folds located southwest of the Whittier fault (Figure 1; Rockwell et al, 1983; Gath et al., 1992).

Recent fault offsets

The southeastern segment of the Whittier fault contains evidence of Quaternary, but not historic, offset. There is a general alignment of valleys and ridges along the fault trace, which is generally marked by a break in slope of hills along the fault (Durham and Yerkes, 1964). Stream drainages have been deflected to the right across the fault. Although some of the deflection can be attributed to fault movement, some of the deflection may be the result of the drainages following the fault because of the more easily erodable rocks along the fault zone. Apparent stream deflections could be greater than true slip of the

fault (Durham and Yerkes, 1964). Sedimentary beds 140 ka in age, within river terraces of the Santa Ana River canyon, have been offset by 400 meters, giving an average late Quaternary slip rate of 2 to 3 mm/yr, with a 10:1 ratio of right-lateral to reverse slip (Rockwell et al, 1988; Gath et al., 1988; Gath, 1997). The uplift rate of the southern Puente Hills in 0.57±0.05 mm/yr (Figure 1; Gath, 1997). Trenching along the fault has uncovered evidence of recent offsets, including faulted Holocene alluvium dated at 1400 to 2200 years BP (Gath et al., 1988; Working Group on California Earthquake Probabilities, 1995).

STRATIGRAPHY

The strata of the northwestern Puente Hills along the Whittier fault consist of middle Miocene volcanic and Miocene to Quaternary sedimentary rocks that unconformably overlie a Mesozoic granitic and metamorphic basement (Figure 3; Yerkes, 1972; Yerkes and Campbell, 1979; Yeats and Beall, 1991; Tsutsumi, 1996).

Correlation of strata across the Los Angeles basin are based on biostratigraphic benthic foraminiferal zones (Blake, 1991). Kleinpell (1938) separated the late Oligocene to late Miocene into six stages based on foraminiferal associations. These stages are the Zemorrian, Saucesian, Relizian, Luisian, Mohnian, and Delmontian. The Pliocene through Pleistocene was divided into four stages by Natland (1952). These are the Repettian, Venturian, Wheelerian, and Hallian. Kleinpell (1980) later refined his biostratigraphic zonation of foraminifers to the Mohnian and Delmontian stages. The correlation of these biostratigraphic stages with the lithology of the study area is shown in Figure 3. Correlations in the Los Angeles basin for the middle to late Miocene (Luisian to Delmontian stages) are also based on the six divisions from A-F of Wissler (1943) (Figure 3). These divisions are based on key benthic foraminifera species (Blake, 1991).

In the study area complications arise from correlations based on foraminifera. Floyd and Maxwell (1964) noted the appearance of wedges of reworked Miocene material in Pliocene footwall strata, which they believed resulted from motion on the Whittier fault. Part of the problem is that sediment deposited into the Los Angeles basin from sources in the San Gabriel Mountains flowed across this area near the Whittier Narrows (Redin,

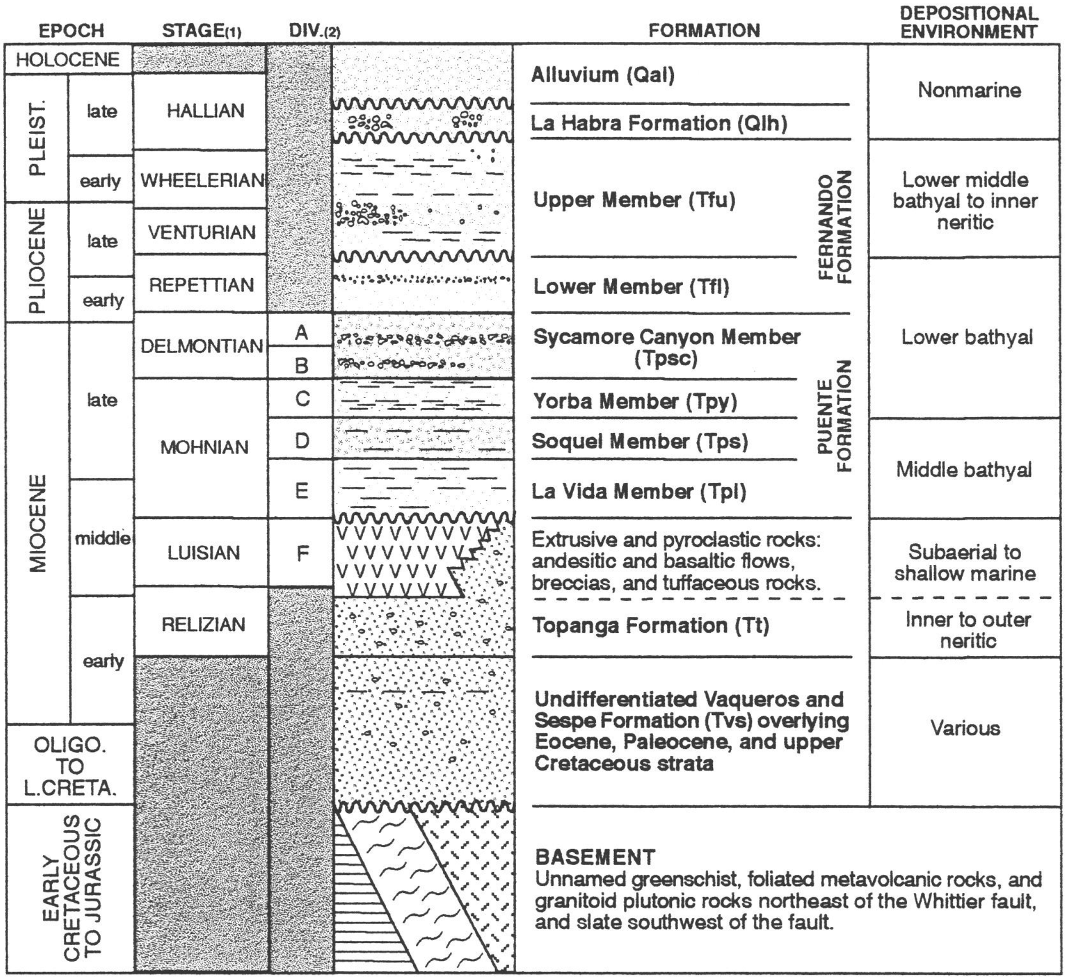


Figure 3 Composite stratigraphic section of the northwestern Puente Hills. No scale implied by formation thicknesses (after Yerkes, 1972, and Blake, 1991).

1 Pleistocene and Pliocene stages from Natland (1952), Miocene stages from Kleinpell (1938,1980)

2 Miocene divisions from Wissler (1943)

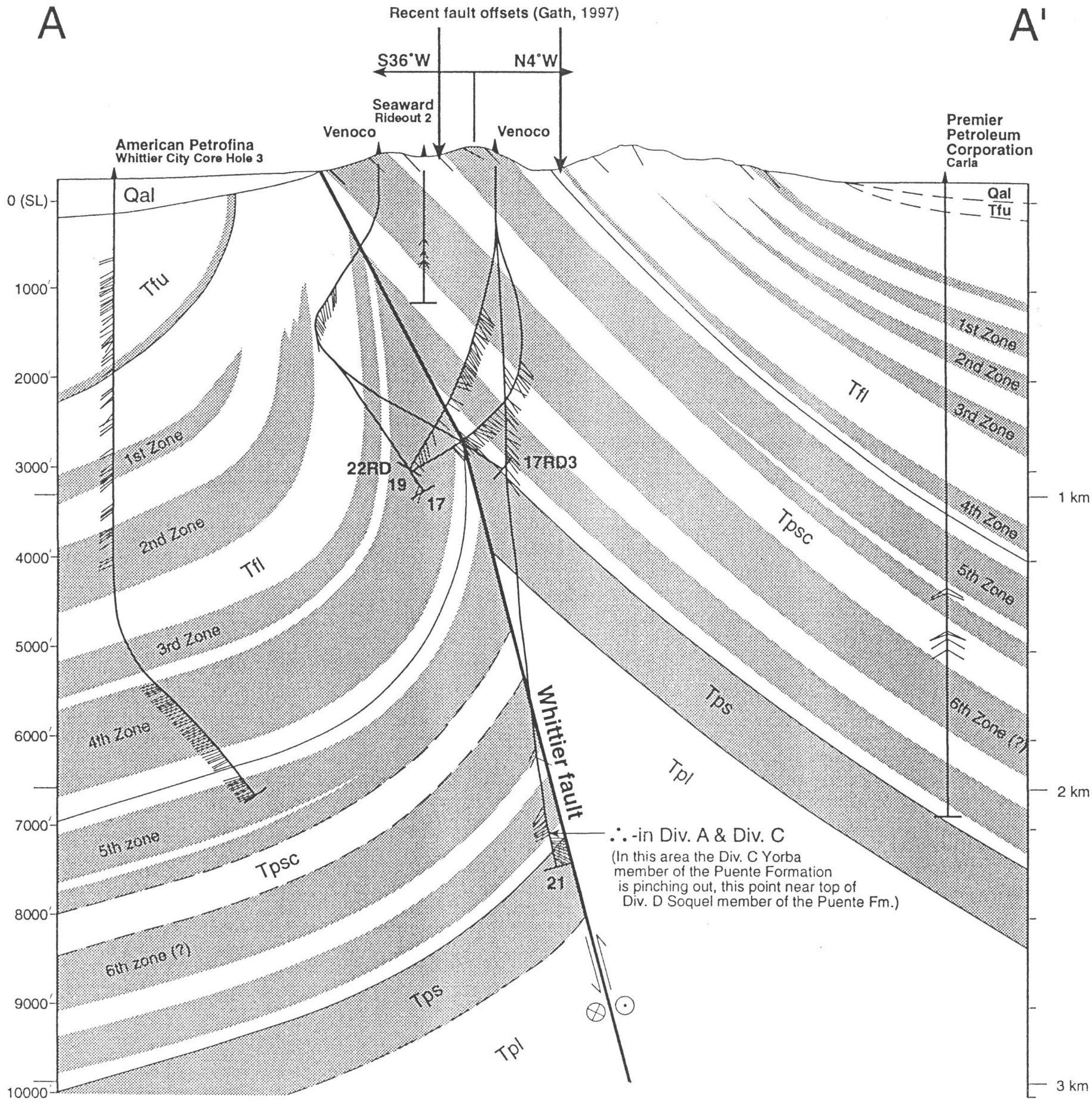


Figure 4 Cross section A-A' through the northwestern part of the Whittier Heights area of the Whittier oil field. Location of cross section on Figure 2. No vertical exaggeration. Shading represents coarser grained sandstone units in the Puente and Fernando Formations. Zone designations correlate to producing zones in the Central area of the Whittier oil field. Key to abbreviations: Qal-alluvium; Tfu-upper member, Fernando Fm.; Tfl-lower member, Fernando Fm.; Tpsc-Sycamore Canyon member, Puente Fm.; Tps-Soquel member, Puente Fm.; Tpl-La Vida member, Puente Fm.; ∴-benthic foram paleo data.

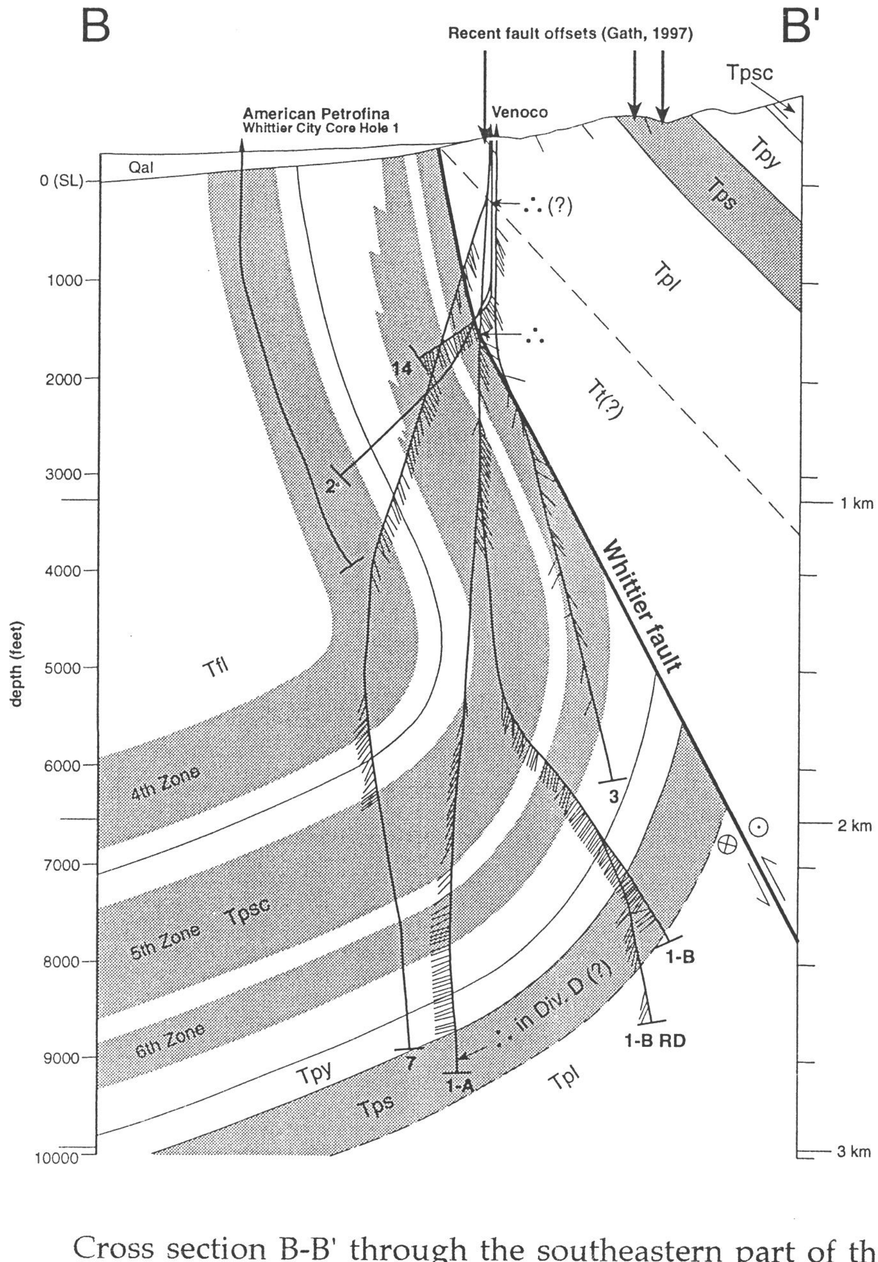


Figure 5 Cross section B-B' through the southeastern part of the Whittier Heights area of the Whittier oil field. Location of cross section on Figure 2. No vertical exaggeration. Shading represents coarser grained sandstone units in the Puente and Fernando Formations. Zone designations correlate to producing zones in the Central area of the Whittier oil field. Key to abbreviations: Qal-alluvium; Tfu-upper member, Fernando Fm.; Tfl-lower member, Fernando Fm.; Tpsc-Sycamore Canyon member, Puente Fm.; Tpy-Yorba member, Puente Fm.; Tps-Soquel member, Puente Fm.; Tpl-La Vida member, Puente Fm.; Tt-Topanga Fm.; ∴-benthic foram paleo data.

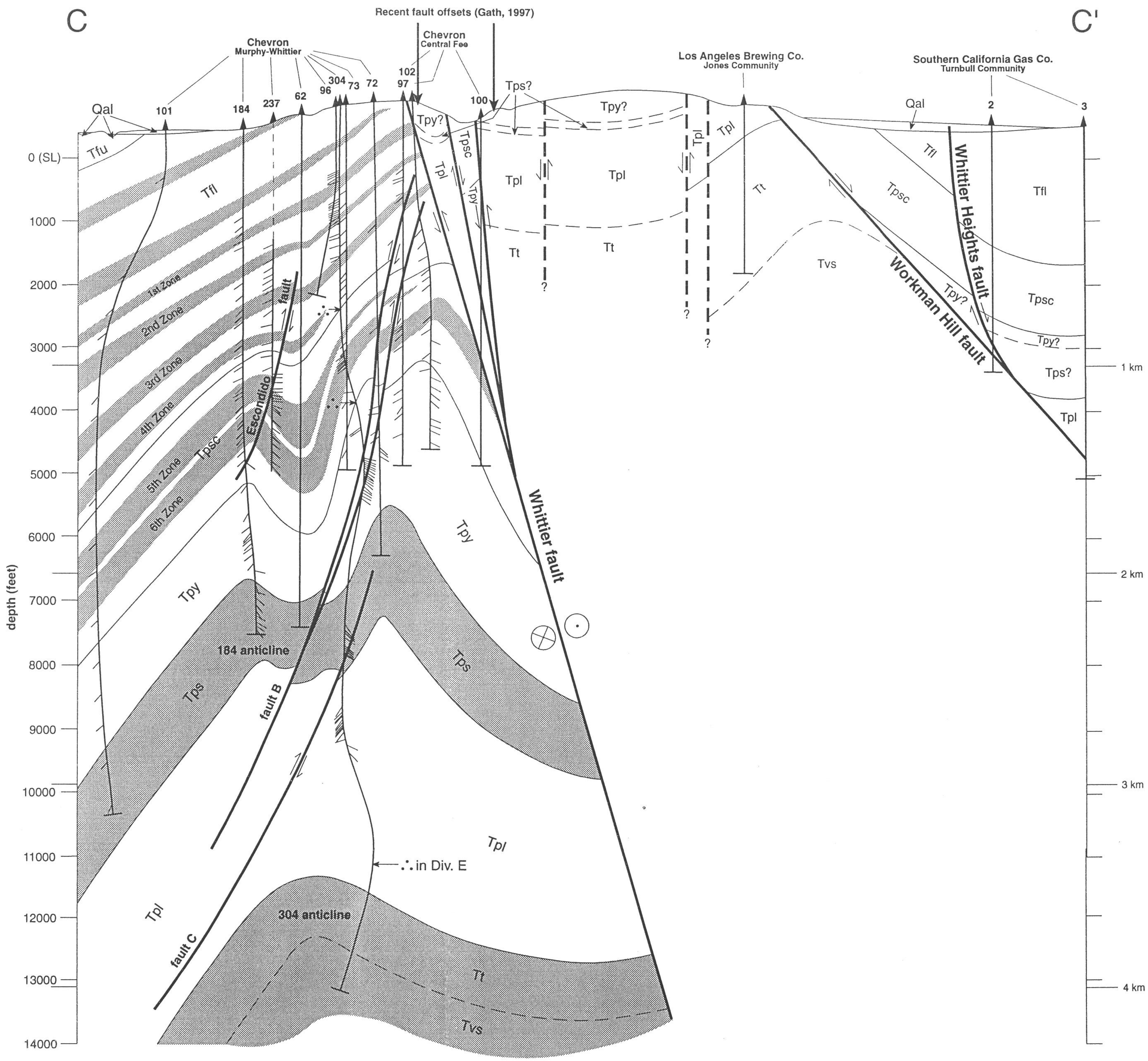


Figure 6 Cross section C-C' through the Central area of the Whittier oil field. Location of cross section on Figure 2. No vertical exaggeration. Shading represents coarser grained sandstone units in the Puente and Fernando Formations. Zone designations correlate to producing zones in the Central area of the Whittier oil field. The section northeast of the Whittier fault is from Yerkes (1972). Key to abbreviations: Qal-alluvium; Tfu-upper member, Fernando Fm.; Tfl-lower member, Fernando Fm.; Tpsc-Sycamore Canyon member, Puente Fm.; Tpy-Yorba member, Puente Fm.; Tps-Soquel member, Puente Fm.; Tpl-La Vida member, Puente Fm.; Tt-Topanga Fm.; Tvs-undifferentiated Vaqueros and Sespe Fm.; ∴-benthic foram paleo data.

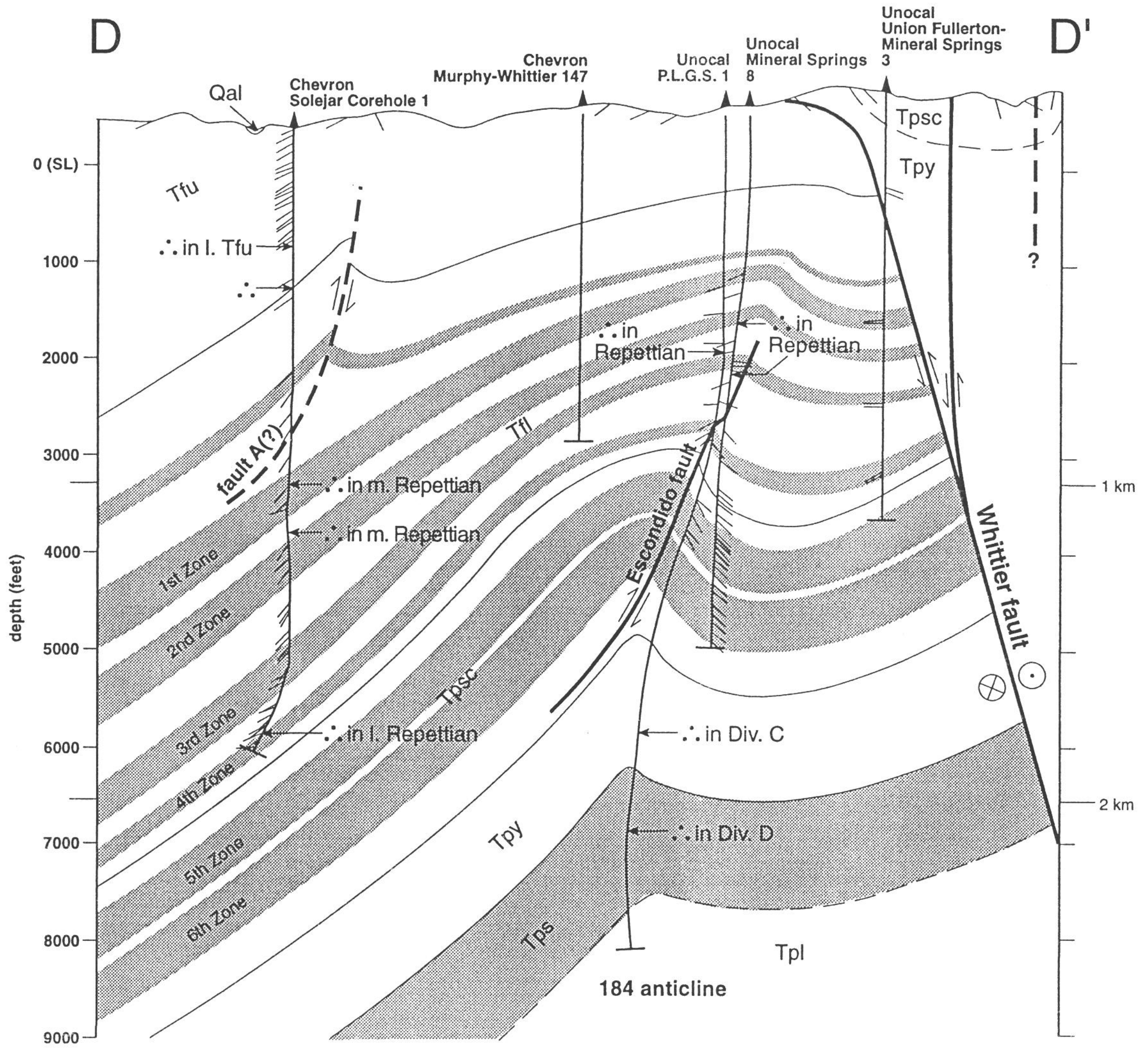


Figure 7 Cross section D-D' through the La Habra area of the Whittier oil field. Location of cross section on Figure 2. No vertical exaggeration. Shading represents coarser grained sandstone units in the Puente and Fernando Formations. Zone designations correlate to producing zones in the Central area of the Whittier oil field. The section east of the Whittier fault is based on information from Yerkes (1972). Key to abbreviations: Qal-alluvium; Tfu-upper member, Fernando Fm.; Tfl-lower member, Fernando Fm.; Tpsc-Sycamore Canyon member, Puente Fm.; Tpy-Yorba member, Puente Fm.; Tps-Soquel member, Puente Fm.; Tpl-La Vida member, Puente Fm.; ∴-benthic foram paleo data.

1991). The active submarine environment may not have been suitable for foraminifera to thrive. Most of the paleontologic data in this area is based on rare occurrences of forams in the samples. During this study, inconsistencies in paleontologic data, mainly from wells in the Rideout Heights area of the Whittier oil field near the Whittier fault, led to the correlation of wells based mainly on lithology. The lithologic correlations in these wells were then tied to lithologic and paleontologic data in wells that appeared to be more reliable to the southeast, farther from the fault.

In this section all depths will be in meters except for those related to well data where measured depths will be presented in both meters and feet.

Basement

The basement consists of an unnamed greenschist that is believed by Yerkes (1972) to be correlated with the Santiago Peak Volcanics in the Santa Ana Mountains, and biotite-quartz diorite and granodiorite of the Southern California batholith (Yerkes et al., 1965; Yerkes, 1972). These basement rocks have been reached in several wells throughout the Puente Hills and surrounding area, and are exposed at the surface in the northern Puente Hills (Daviess and Woodford, 1949; Yerkes, 1972). The basement west of the Whittier fault consists of metasedimentary rocks that correlate with the Santa Monica Slate in the central Santa Monica Mountains (Yerkes et al., 1965; Yerkes and Campbell, 1979; Tsutsumi, 1996). According to Yerkes (1972) about 3.66 km of structural relief exists on the basement surface across the Whittier fault, with the basement being shallower northeast of the Whittier fault.

Late Eocene to early Miocene

In the study area, late Eocene to early Miocene strata are assigned to the undifferentiated Vaqueros and Sespe Formation (Figure 3). These strata are assumed to overlie Eocene, Paleocene, and Upper Cretaceous sedimentary rocks similar to those exposed in the Santa Ana Mountains to the southeast. In the Puente Hills the Vaqueros and Sespe Formations cannot be separated. The undifferentiated Vaqueros and Sespe consists of non-marine red mudstone, sandstone, and pebbly sandstone characteristic of the Sespe Formation, and has interbeds of marine fossil bearing strata characteristic of the Vaqueros Formation (Yerkes, 1972). Daviess and Woodford (1949) have questionably correlated the strata at the bottom of the Southern California Gas Company Turnbull Community No. 2 and No. 3 wells [sec 13, T2S, R11W] with the Sespe (Figure 6). The beds in the well comprise a nonfossiliferous, brown, gray, and green fine conglomerate, sandstone, and claystone.

In the central area of the Whittier oil field [sec 26, T2S, R11W], southwest of the Whittier fault, strata in Chevron Murphy-Whittier 304 well that have been correlated with the Sespe Formation consist of poorly sorted, very fine to medium grained, red to dark brown sandstone with minor amount of light brown to reddish claystone and siltstone, reworked volcanics, and scattered pyrite and unidentified greenish grains. There is some doubt about the correlation of these beds with the Sespe. At the time of deposition of this unit, the environment was subaerial to shallow marine.

Early to middle Miocene

Conformably overlying the undifferentiated Vaqueros and Sespe Formation is the Topanga Formation (Figure 4). The Relizian to Luisian stage (Division F) Topanga Formation consists of marine siltstone, fine-grained feldspathic sandstone, pebbly sandstone, indurated black siltstone, and conglomerate (Yerkes, 1972; Blake, 1991). In the Puente Hills, the Topanga Formation contains middle Miocene mollusks, Luisian fish scales, and Relizian foraminifera assemblages (Daviess and Woodford, 1949; Blake, 1991).

The Topanga Formation is reached by the Chevron Murphy-Whittier 304 and Los Angeles Brewing Co. Jones Community wells (Figure 6). In the Murphy-Whittier 304 well, strata correlated with the Topanga Formation are mainly massive sandstone with interbedded claystone and minor amounts of siltstone, basalt, and limestone. Scattered grains of biotite, muscovite, and chlorite are present. The sandstone is generally poorly sorted, very fine to medium grained, and friable to hard with a high pyrite content. No characteristic foraminifera of Division F have been found in this interval in the 304 well.

Overlying and interbedded with the Topanga Formation are andesitic and basaltic flows, breccias, and tuffaceous rocks that correlate with the El Modeno Volcanics (Gourley, 1971; Yerkes, 1972; Blake, 1991). Southwest of the Whittier fault, in the Murphy-Whittier 304 well, the Topanga Formation is identified by the appearance of these volcanics, largely as scattered grains and thin interbeds. Northeast of the Whittier fault, in the Jones Community well, based on work by Yerkes (1972), a volcanic tuff approximately 300 meters thick overlies the Topanga Formation (Yerkes, 1972). This results in a thicker early to middle Miocene sequence northeast of the Whittier fault. This may be explained by normal-fault offset on the Whittier fault during deposition of the volcanic unit, causing strata northeast of the fault to be thicker than strata to the southwest. Normal offset on the Whittier fault during this time corresponds with a period of regional extension (Yeats, 1976; Campbell and Yerkes, 1976; Wright, 1991; Schneider et al., 1996), and possibly signals the time of initiation of the Whittier fault in this area.

The Topanga Formation was deposited near shore in an inner-to-outer neritic environment (less than 100 meters), where shallow-water marine strata interfingered with subaerial volcanic rocks (Yerkes, 1972; Blake, 1991).

Middle to late Miocene

Unconformably overlying the Topanga Formation and volcanic rocks is the middle to late Miocene Puente Formation. The Puente Formation is a marine clastic sequence divided into the La Vida, Soquel, Yorba, and Sycamore Canyon members. The Puente Formation in the Puente Hills is up to 3900 meters thick (Blake, 1991; Critelli et al., 1995). The Puente Formation consists of thick turbidite deposits that are part of a submarine Puente fan complex located in the northeastern part of a subsiding basin (Figure 8; Conrey, 1967; Redin, 1991; Critelli et al., 1995).

La Vida member

The lowest member of the Puente Formation is the lower Mohnian (Division E) La Vida member (Figure 3). The La Vida member is a platy, light-gray to buff calcareous siltstone with thin interbedded micaceous siltstone and fine grained silty feldspathic sandstone with minor amounts of

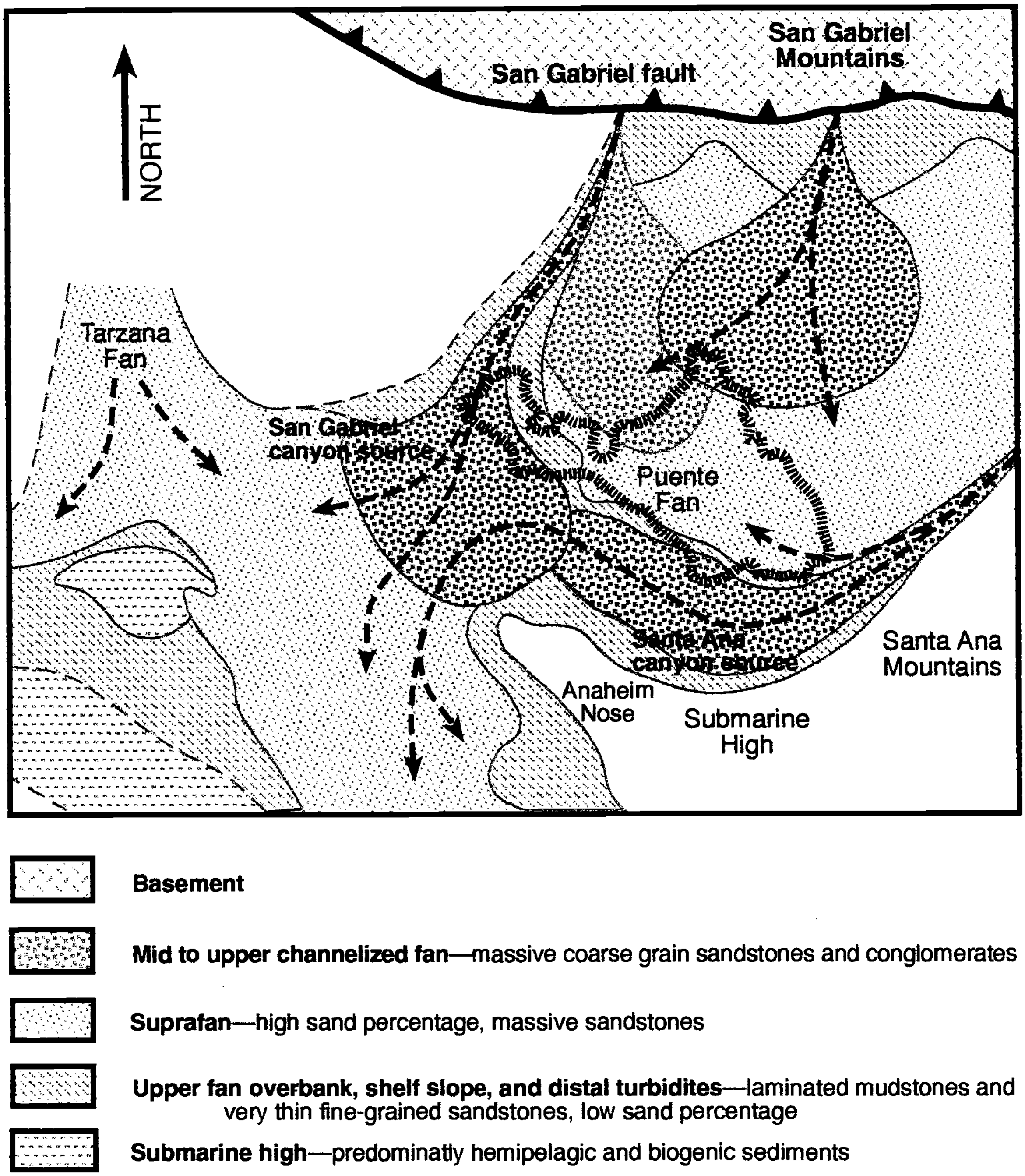


Figure 8 Diagram showing the depositional setting for the Puente Formation during the late Miocene. The Puente Formation consists of a series of coalesing submarine fans derived from sources mainly in the San Gabriel Mountains. Dashed-pattern line shows the approximate location of the Puente Hills (after Redin, 1991, and Critelli et al., 1995).

tuff, shale and dolomite (Gourley, 1971; Yerkes, 1972; Blake, 1991). Near the Whittier fault this member is sheared and tightly folded (Yerkes, 1972). This member contains the characteristic Division E benthic foraminifers *Bulimina uvigerinaformis* and *Bolivina modeloensis* (Daviess and Woodford, 1949; Blake, 1991).

The La Vida member is reached by several wells in the study area, but only the Chevron Murphy-Whittier 304 well penetrates the entire member (Figure 6). In the Murphy-Whittier 304 well the La Vida member consists of a slightly sandy claystone near the top, becoming mainly a firm to moderately hard, massive, slightly calcareous siltstone with minor amounts of claystone, dolomitic limestone, and volcanic tuff downsection. *Bulimina uvigerinaformis* appears in the well from 3785.4 meters (12420 feet) to the base of the member. The base of the La Vida member is mainly sandstone with thin interbeds of siltstone (Noble, 1966). This represents a fining-upward sequence indicating an apparent rise in sea level that was most likely due to basin subsidence. By the end of La Vida deposition, the water depth was middle bathyal (>100 meters). Near the Whittier fault zone, the La Vida member is intruded by sills of diabase up to 60 meters (200 feet) thick (Daviess and Woodford, 1949; Yerkes, 1972), indicating that this was a zone of weakness through which the diabase could pass.

Soquel member

Conformably overlying the La Vida member is the middle Mohnian (Division D) Soquel member of the Puente Formation (Figure 3). In the Whittier oil field area this member is a producing zone known as the 184 Sand (Floyd and Maxwell, 1964; Noble, 1966). The Soquel member is a poorly-sorted, massive, fine to coarse grained feldspathic sandstone and pebbly sandstone with minor interbedded brown shale, calcareous siltstone, and conglomerate (Daviess and Woodford, 1949; Gourley, 1971; Yerkes, 1972; Blake, 1991). The conglomerate beds contain clasts of mainly andesitic and other volcanic rocks, with minor amounts of granitic clasts south of Turnbull Canyon (Daviess and Woodford, 1949). Source for these clasts is probably the San Gabriel Mountains to the northeast. Index fauna for this member have not been found in the Puente Hills, and the Soquel member has only minor faunal variations with respect to the overlying Yorba member (Blake, 1991). Near the base of the Soquel member, siltstone content increases downsection (Gourley, 1971).

In the Murphy-Whittier 304 well, the Soquel member is a massive, very fine- to fine-grained, well-sorted, slightly to moderately calcareous sandstone with thin interbeds of siltstone. The sandstone has some soft clay matrix in places, is friable to slightly hard, and has scattered grains of biotite, muscovite, and pyrite. Both the Soquel and the underlying La Vida were deposited in an upper- to middle-bathyal environment, with the water depth increasing from 300 meters at the beginning of La Vida deposition to 1500 meters at the end of Soquel deposition (Yerkes, 1972). Both members were deposited on the distal portion of the Puente fan by turbidity currents from the east and northeast (Floyd and Maxwell, 1964; Yerkes, 1972; Redin, 1991; Critelli et al., 1995).

The appearance of this coarser grained member above the fining upward sequence of the La Vida member, especially in a basin undergoing continued subsidence, is probably due to a change in the source area. The Soquel member has a higher percentage of metamorphic grains and a lower percentage of volcanic material than the underlying La Vida member (Critelli et al., 1995), which may reflect a change in the source area located in the San Gabriel Mountains. Based on work by Critelli and others (1995), the turbidites that make up these formations were deposited by several smaller coalescing fans derived from sources in the San Gabriel Mountains (Figure 8). The increase in clast size and change in composition could be due to material being deposited into this area from a more proximal source.

In Figure 6 the thickness of the Soquel member in both the Chevron Murphy-Whittier 304 and Southern California Gas Co. Turnbull Community No. 3 wells is similar. Figure 4 shows that the Soquel member is generally uniform in thickness on both sides of the Whittier fault. This indicates that there may have been little if any deformation in this area at this time.

Yorba member

Conformably overlying the Soquel member is the upper Mohnian (Division C) Yorba member of the Puente Formation (Figure 3). This member is finer grained and has a different composition than the Soquel member. The Yorba member is a poorly- to well-bedded brown to black, clayey to calcareous, micaceous siltstone, mudstone, and sandy siltstone with interbedded sandstone and dolomite beds, along with some beds of well-indurated pebble-cobble conglomerate that weathers white in outcrop (Floyd and Maxwell, 1964; Gourley, 1971; Yerkes, 1972; Blake, 1991). The Yorba member contains more volcanic and less metamorphic detritus than the Soquel member, making it similar in composition to the La Vida member (Critelli et al., 1995). A change in the source area may have resulted in sediments being derived once again from a more distal source. The Yorba member contains the characteristic Division C foraminifer Bolivina *hughesi* (Blake, 1991). Like the La Vida member, the Yorba member is tightly folded near the Whittier fault (Yerkes, 1972).

In the Murphy-Whittier 304 well the Yorba member consists of interbedded sandstone, siltstone, and minor claystone and dolomite beds with traces of biotite and pyrite. Sand grains are very fine to medium in size and fairly well sorted. In the 304 well, the type foraminifer *Bolivina hughesi* is present, although not abundant. In the well the Yorba member can be picked based on the foraminifera assemblage present. The Yorba member was deposited in a lower bathyal environment, with water depths greater than 2400 meters (Yerkes, 1972). Transport direction for this member is from the north to northeast (Yerkes, 1972).

The distribution of the Yorba member is not uniform in the study area. The Yorba member thins and pinches out to the northwest (Figure 13). As shown in Figures 6 and 7, the Yorba member in the southeastern part of the study area is approximately 300 meters thick and is more or less uniform in thickness. Figure 5 shows that the Yorba member northeast of the Whittier fault in the northern part of the study area is approximately 180 meters thick, and approximately 100 meters thick southwest of the fault. In Figure 4 the Yorba member, if present, is much thinner. The thinning of this member northward may be the result of folding of the Rideout Heights anticline.

Sycamore Canyon member

Conformably overlying the Yorba member, as well as unconformably overlying the Soquel member in the northwestern Puente Hills west of where the Yorba member pinches out (Figure 13), is the uppermost member of the Puente Formation, the Delmontian (Division A and B) Sycamore Canyon member (Figure 3). The Sycamore Canyon member differs from the Yorba member by an overall increase in grain size, including the deposition of several conglomerate interbeds, and an increase in abundance of hornblende grains (Critelli et al., 1995). The Sycamore Canyon member consists of massive gray micaceous sandy siltstone, platy siliceous siltstone, and fine- to coarse-grained sandstone with pebble-cobble conglomerate lenses (Gourley, 1971; Yerkes, 1972; Blake, 1991). The Sycamore Canyon conglomerate tends to weather to a rusty brown color and commonly forms steep, erosionally-resistant outcrops and cliffs (Gourley, 1971; Yerkes, 1972; Leighton and Associates, 1992). Clasts of biotite granite, quartz monzonite, and gneiss in the Sycamore Canyon conglomerate indicate a source in the San Gabriel Mountains (Figures 1 and 8; Daviess and Woodford, 1949; Yerkes, 1972). The composition changes may also involve a change to a more proximal source area (Figure 8), and an increase in the uplift rate and deeper erosion of the San Gabriel Mountains caused by a change from regional extension to contraction at that time (Wright, 1991; Yeats and Beall, 1991; Critelli et al., 1995). This member contains *Bolivina forminata* and *Bolivina obliqua,* characteristic for the stage (Blake, 1991).

South of the Whittier fault, in the Turnbull Canyon area, the Sycamore Canyon member consists of thick-bedded, coarse-grained to pebbly sandstone with siltstone interbeds (Gourley, 1971; Yerkes, 1972). Conglomerate similar to that exposed north of the Whittier fault is missing in this area. This may be an indication that the distribution of the conglomerates was affected by folding of the Rideout Heights anticline, with the conglomerate lensing out toward the axis of the anticline, and are therefore not present in this outcrop (Figure 5).

In the Murphy-Whittier 304 well, the Sycamore Canyon member consists of very-fine- to medium-grained white to light gray sandstone interbedded with siltstone. The sandstone has some clay matrix, and minor amounts of dolomite with scattered grains of biotite and muscovite. The 304 well contains *Bolivina forminata* at 951 meters (3120 feet), marking the top of the Delmontian. In the well, conglomerate is absent. According to Redin (1991) the Delmontian conglomerates are channelized fan deposits. This area is to the south of the main channel through the Whittier Narrows, and conglomerate was not deposited in this area. The Sycamore Canyon member was deposited in a lower bathyal environment, similar to that of the underlying Yorba member (Yerkes, 1972; Blake, 1991).

Although there was a change to regional contraction, there does not appear to have been any dip-slip offset of the Whittier fault at this time, based on the general uniform thickness of the Sycamore Canyon member on both sides of the fault. In Figure 4 the Sycamore Canyon member is approximately 830 meters thick on both sides of the Whittier fault, thinning only slightly toward the fault, which is most likely a result of broad folding of the Rideout Heights anticline. In Figure 5, the Sycamore Canyon member is approximately 750 meters thick south of the Whittier fault. Here the member is slightly thinner, and may be the result of being located closer to the edge of the main depositional channel.

Farther to the southeast, Figures 6 and 7 show that the Sycamore Canyon member is thinner, approximately 450-500 meters thick, with a more or less uniform thickness except for local changes resulting from folding of the 184 and 304 anticlines.

Pliocene to early Pleistocene

Overlying the Puente Formation is the Fernando Formation. The Fernando Formation is divided into two members; the early to late Pliocene lower Fernando, and the late Pliocene to early Pleistocene upper Fernando (Blake, 1991).

The name Fernando formation was first introduced by Eldridge and Arnold (1907), and included all the Pliocene strata in the Ventura and Los Angeles basin (Blake, 1991; Yeats et al., 1994). In 1924, the name Fernando was raised to group rank, and was used by English (1926) in the Puente Hills for all of the Pliocene rocks including the uppermost part of the Sycamore Canyon member of the Puente Formation (Figure 3; Blake, 1991). In the Los Angeles basin, Pliocene strata cannot be divided based on lithology, so they are divided by benthic foraminifera zones. The lower member of the Fernando Formation corresponds to fauna of the Repettian stage, and the upper member includes fauna of the Venturian and Wheelerian stages of Natland (1952). In this report, the Fernando Formation includes only the strata correlated to the Repettian, Venturian, and Wheelerian stages, and does not include the uppermost part of the Sycamore Canyon member of the Puente Formation, which is Pliocene in age. In other parts of the Los Angeles basin, the lower member of the Fernando Formation correlates with the Repetto Formation, and the upper member correlates with the Pico Formation (Blake, 1991).

Lower Fernando member

The lower member of the Fernando Formation, in the northwestern Puente Hills, conformably overlies the Sycamore Canyon member of the Puente Formation (Figure 3). The Repettian-stage lower Fernando consists of silty sandstone, siltstone, and claystone with pebbly conglomerate lenses (Gourley, 1971; Yerkes, 1972; Blake, 1991). The conglomerate lenses are gray orange to light brown in color and are massive and unsorted (Yerkes, 1972). This member has abundant lower bathyal foraminifera indicative of the Repettian stage of Natland (1952) (Blake, 1991). Among these are *Cibicides mckannai*, *Bulimina rostrata*, and *Hopkinsina nodosa* (Blake, 1991).

In the Murphy-Whittier 304 well, the lower member of the Fernando Formation consists of siltstone and silty to very finely sandy claystone with minor amounts of dolomite, along with limestone, mica, and fine quartz grains, and traces of biotite and pyrite. The siltstone is generally massive, noncalcareous, and firm to hard. In the well, the interval from 270.6 meters (888 feet) to 951 meters (3120 feet) has abundant *Cibicides mckannai*, *Bulimina rostrata*, and *Hopkinsina nodosa* species present.

This member was deposited in a lower-bathyal prograding-shelf and slope environment, with the shelf-slope break along the present location of the southwest margin of the Puente Hills (Blake, 1991). There are unconformities present throughout the lower Fernando, including an extensive erosional unconformity at its top, marking the division with the overlying upper Fernando member (Blake, 1991). These unconformities could correspond to periods of increased folding. Figures 4, 5, 6, and 7 show sands pinching out toward the axes of the Rideout Heights, 304, and 184 anticlines, indicating folding at this time.

Upper Fernando member

In the northwestern Puente Hills, the upper member of the Fernando Formation unconformably overlies the lower Fernando member (Figure 3; Yerkes, 1972; Blake, 1991). The Wheelerian to Venturian stage upper Fernando consists of moderate- to well-cemented, coarse grained, thick bedded to massive, reddish-brown pebbly conglomerate with thin interbedded light-brown sandstone and light-gray siltstone (Daviess and Woodford, 1949; Leighton and Associates, 1992). Clasts of the late Miocene Puente Formation are found throughout the upper member of the Fernando Formation. This member contains foraminifers of a lower middle bathyal environment at its base, shallowing up-section to inner neritic foraminifers at the top of the member, indicating that the upper Fernando represents a basin filling sequence (Blake, 1991). The member thins toward the axis of the Rideout Heights anticline from both the north and south, indicating that folding may have been taking place.

Late Pleistocene to Holocene

The late Pleistocene La Habra Formation unconformably overlies the lower member of the Fernando Formation (Figure 3). The La Habra Formation is a nonmarine flood-plain deposit. The formation consists of olive gray to reddish-brown, sandy to pebbly mudstone, along with reddish-brown to gray earthy sandstone, pebbly sandstone, and a basal conglomerate containing clasts from the Puente Formation (Yerkes, 1972).

In the study area, alluvial fan, stream, and flood-plain deposits overlie parts of the La Habra, Fernando, and Puente formations (Yerkes, 1972). These alluvial deposits are probably late Pleistocene to Holocene in age. The deposits consist of poorly-sorted reddish-brown earthy and clayey gravel, sand, and silt (Yerkes, 1972).

STRUCTURE

Whittier fault

The Whittier fault is part of the Elsinore-Whittier-East Montebello fault system extending northwest from the Mexican border to the Whittier Narrows. The Whittier fault trends west-northwest from its intersection with the Elsinore fault near the Santa Ana River to its intersection with the East Montebello fault at Whittier Narrows (Figure 1). The Whittier fault is the northeastern boundary of the central block of the Los Angeles basin, separating it from the Puente Hills (Yerkes et al., 1965). The fault trends approximately N60°-70°W with a dip of approximately 65°-80° NE (Wright, 1991; Gath, 1997). In the northwestern Puente Hills, the Whittier fault is near or just to the northeast of the southwestern margin of the Puente Hills (Figure 10). Its surface trace is covered by Quaternary alluvium northwest of Turnbull Canyon.

Reverse separation on the northwestern segment of the Whittier fault increases to the south. At the northern end of the study area, the separation on the East Montebello fault based on the offset of the top of the Sycamore Canyon member of the Puente Formation is zero, with the fault having normal separation to the north (Figure 9). Just south of the intersection of the East Montebello and Whittier faults, the separation is at least 1300 meters based on the separation of the base of the Soquel member of the Puente Formation (Figure 4). Figure 6 shows approximately 3650 meters of separation on the Whittier fault based on the separation of the base of the La Vida member of the Puente Formation in the central area of the Whittier oil field.

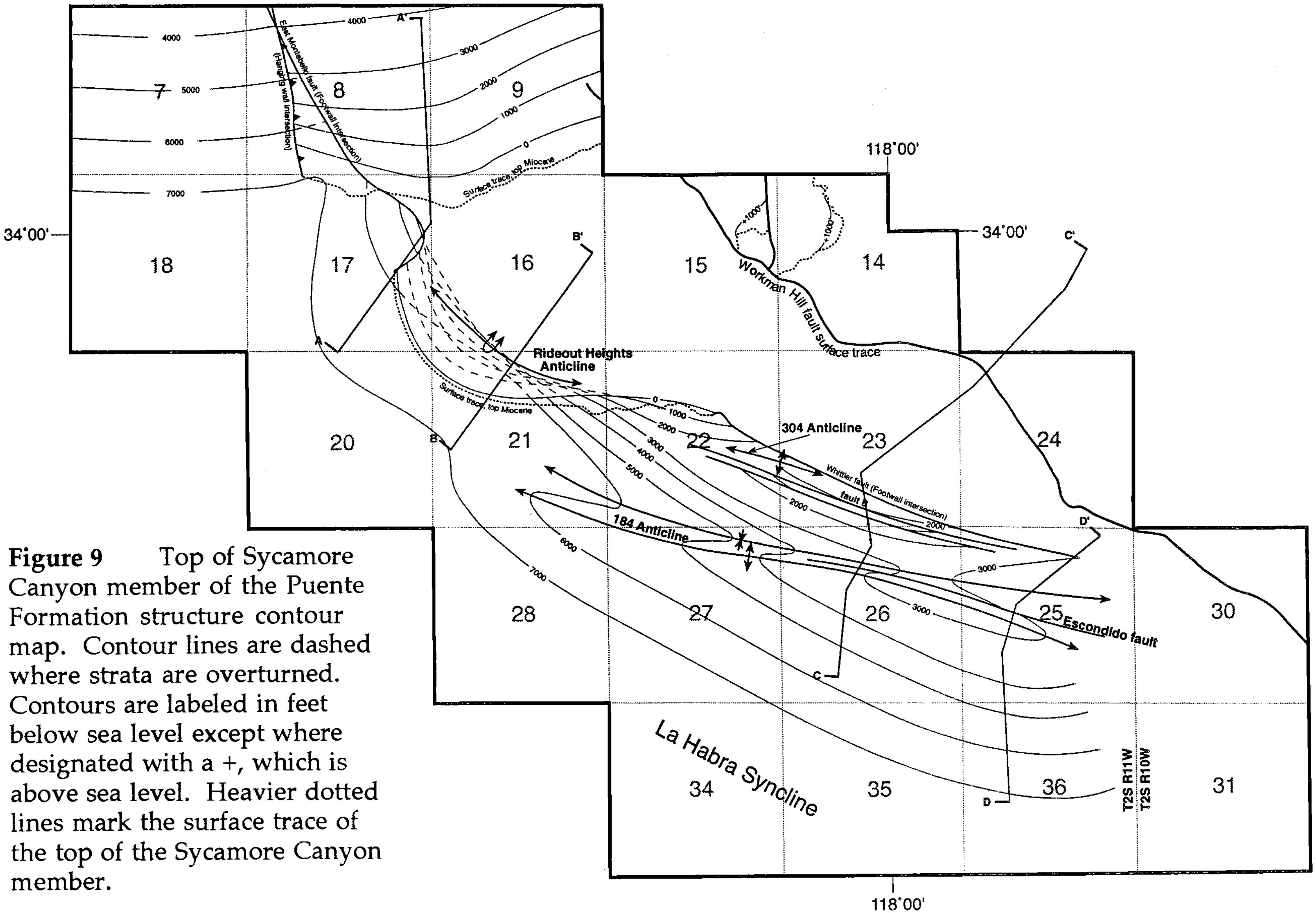


Figure 9 Top of Sycamore Canyon member of the Puente Formation structure contour map. Contour lines are dashed where strata are overturned. Contours are labeled in feet below sea level except where designated with a +, which is above sea level. Heavier dotted lines mark the surface trace of the top of the Sycamore Canyon member.

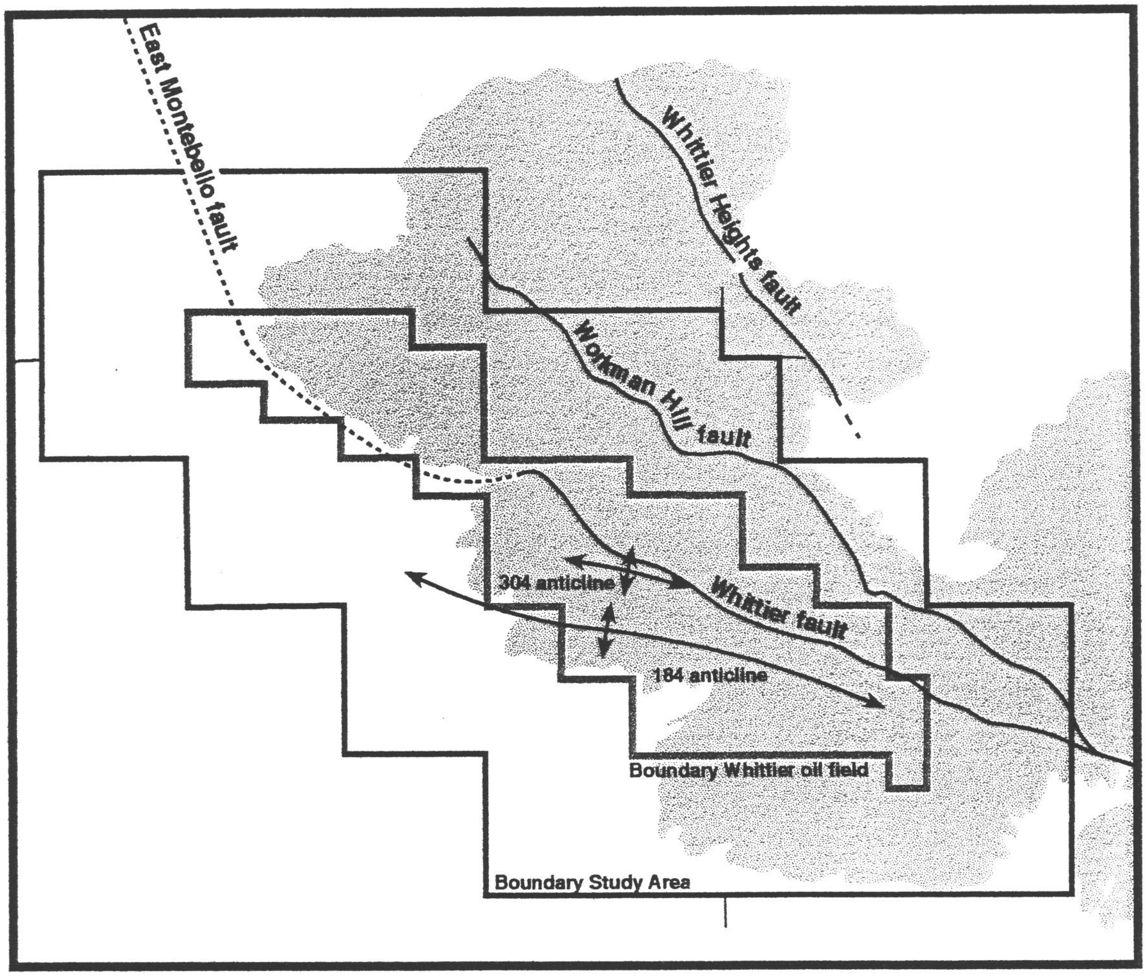


Figure 10 Map of the northwestern Puente Hills. Shading indicates the Puente Hills. Solid fault lines indicate where the major faults are present at the surface, dashed where uncertain, and dotted where projected to the surface through overlying alluvium.

Puente Hills uplift

Uplifted terraces in the Santa Ana River canyon are evidence that the Puente Hills are uplifting (Gath, 1995). The uplift rate of the Puente Hills based on the terraces is 0.57±0.05 mm/yr (Figure 1; Gath, 1995). The uplift of the Puente Hills may be the result of the orientation of the Whittier fault. In the Elsinore-Whittier-East Montebello fault system the East Montebello and Elsinore faults have similar northwest strikes, while the Whittier fault strikes west-northwest (Figure 1). In this fault system, the Whittier fault forms a large restraining bend, which results in the uplift of the Puente Hills. Where the Whittier fault ends, at its junction with the East Montebello fault, the Puente Hills also end as strata dip north beneath the Whittier Narrows (Figure 9). Similarly, the Puente Hills terminate eastward at Santa Ana Canyon, where the Whittier fault turns southeast and becomes the Elsinore fault.

Workman Hill and Whittier Heights faults

The Workman Hill and Whittier Heights faults are located northeast of the Whittier fault in the Puente Hills (Figure 10). The Workman Hill fault, and possibly the Whittier Heights fault as well, splay off the Whittier fault just southeast of the study area. These faults strike more northerly than the Whittier fault. These faults are more or less parallel to each other with dips to the northeast from 35° to 90° at the surface, decreasing with depth (Figure 6; Daviess and Woodford, 1949). Both of these faults have normal separation of 700 to 900 meters near the middle with offsets decreasing toward their ends (Daviess and Woodford, 1949). The origin of these faults is discussed in more detail in relation to the offset of the Whittier fault.

Rideout Heights anticline

The Rideout Heights anticline trends N55°W from the mouth of Turnbull Canyon through the Rideout Heights area of the Whittier oil field (Figure 9). Figures 4 and 5 are drawn through the anticline and show evidence of its development. The anticline verges to the southwest; the southwest limb is overturned, and the northeast limb is normally dipping. The Whittier fault cuts along the hinge of the anticline, offsetting strata in the fold by at least 2100 meters at its northern end (Figure 4). This separation is greater toward the middle of the anticline, as shown in Figure 5.

Initial folding of the Rideout Heights anticline appears to have occurred during deposition of the Pliocene Fernando Formation. The Fernando Formation thins toward the Whittier fault from both the northeast and southwest. Northeast of the Whittier fault, sands near the base of the Pliocene assigned to the 4th zone thin, and sands of the 1st, 2nd, and 3rd zones pinch out toward the fault. Southwest of the Whittier fault, all of the sand zones as well as the Fernando Formation are thicker, which may be a result of folding of the La Habra syncline and possibly asymmetric folding of the Rideout Heights anticline. In the southwest limb, all sand zones thin toward the fault, with the 1st and 2nd zone sands pinching out.

304 and 184 anticlines

The 304 and 184 anticlines trend northwest through the Central and La Habra areas of the Whittier oil field (Figures 9 and 10). Both anticlines are northeast verging (Figures 6 and 7).

Strata underlying and including the 6th zone sands of the Sycamore Canyon member appear to be more or less uniform in thickness, indicating that folding was not taking place during this time. Folding of the 304 anticline appears to have initiated during deposition of the upper part of the Sycamore Canyon member near the end of the Miocene, based on thinning of the 5th zone sands in the southwest limb of the fold (Figure 6). Folding of the 304 anticline continued at least up through the deposition of the 2nd zone sands in the Pliocene, which thin as they approach the Whittier fault. The overlying 1st zone sands do not show thinning toward the crest of the anticline. The northeast limb of the fold has since been cut by the Whittier fault.

The 184 anticline formed at approximately the same time as the 304 anticline. Evidence for this is thicker strata between and including the 5th zone sands up to but not including the 3rd zone sands in the syncline between the 184 and 304 anticlines (Figure 6). Figure 7 also shows the same strata thickening in the syncline between the 184 anticline and the Whittier fault. The 4th zone sands thin slightly over the axis of the 184 anticline, indicating deposition during folding (Figures 6 and 7). Folding of the 184 anticline appears to have stopped by the time of deposition of the 3rd zone sands. The 184 anticline is secondary to the 304 anticline, forming in the southwest limb of the 304 anticline.

Cutting up along or near the axes of the 184 and 304 anticlines are several southwest-dipping faults (Figures 6 & 7). This type of faulting is common, resulting from flexural slip folding and weakened strata along the hinge of the fold. During flexural slip folding , the upper layers of strata move toward the hinge of the anticline by slip along bedding planes. The fault cuts upsection through bedding at a low angle, then continues to cut up through the weakened strata in the hinge of the fold (Jaroszewski, 1984, p. 490).

DISCUSSION

Origin of the Whittier oil field anticlines

Based on the change in thickness of strata, thinning toward the axes of the Rideout Heights, 304, and 184 anticlines, folding initiated near the end of the Miocene. The folding continued through the Pliocene and possibly into the Pleistocene. The late Miocene through the Pleistocene corresponds with a period of regional contraction.

The Rideout Heights anticline appears to be a fault propagation fold resulting from a northeast dipping fault. The development of the Rideout Heights anticline may be similar to the Las Cienegas anticline in the northern Los Angeles basin, which is described as a basement-involved compressive structure (Schneider, 1994). The kinematic development of this type of fold is shown in Figure 11 (Narr and Suppe, 1994). The mechanism for the formation of the 304 anticline is not clearly evident, but two possible methods will be discussed: bedding-plane shear folding and blind thrusting.

Bedding-plane shear folding

The 304 anticline resembles the East Beverly Hills anticline located in the northern Los Angeles basin. Schneider and others (1996) described the formation of the East Beverly Hills anticline as an out-of-the-syncline or rabbit-ear fold on the flank of a monocline. According to Schneider and others (1996), as the monocline formed, a space problem developed due to excess bed lengths in the lower axis of the fold. To accommodate this problem, bedding-plane shear folding and faulting occurred, resulting in the formation of the East Beverly Hills anticline.

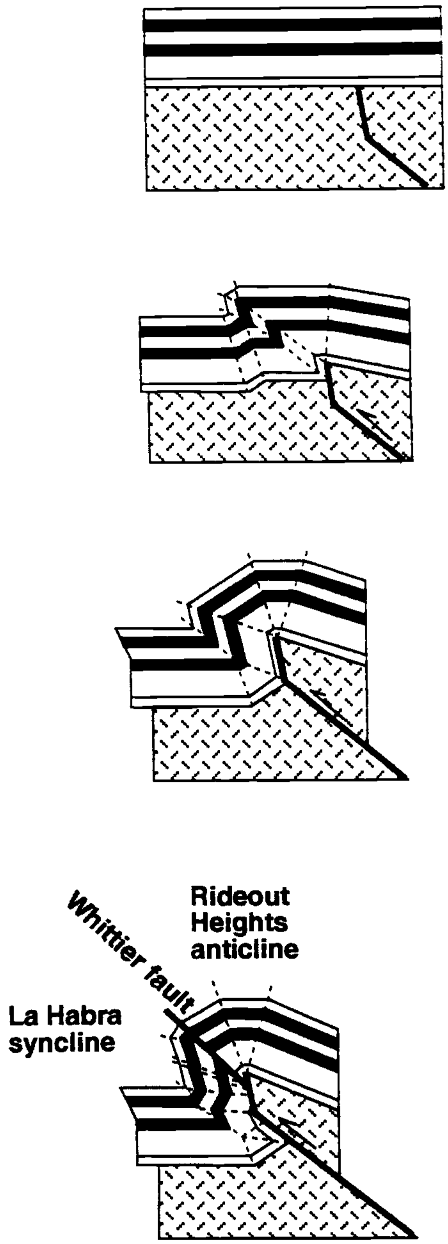


Figure 11 The sequential kinematic development of a basement-involved compressive fault propagation fold structure. This may be similar to the development of the Rideout Heights anticline (after Narr and Suppe, 1994).

A similar situation could have taken place with the formation of the 304 anticline. The 304 anticline is located in the northeastern limb of the La Habra syncline. The La Habra syncline is a northwest-southeast structure located between the Puente Hills and Coyote Hills (Figure 1). As shown in Figures 4, 5, 6, 7, and 9, the Pliocene and younger sediments in the study area thicken toward the center of the syncline, indicating that the La Habra syncline was growing during this time. As folding of the syncline continued, a space problem developed, causing slip to take place along bedding planes as strata higher in the sequence moved away from the axis of the fold. This resulted in bedding-plane shear faulting and folding, and the formation of the 304 anticline. The 184 anticline appears to be the result of bedding-plane shear in the southwest limb of the 304 anticline. Evidence for this type of bedding-plane shear is present in the 304 and 184 anticlines, as shown by the faults cutting along or near the hinge of the folds. As shown in Figures 6 and 7, these faults start as bedding slip, then propagate upsection.

One of the identifying characteristics of this type of folding is the structural thickening of strata in the core of the fold due to bedding-plane shear (Schneider et al., 1996). In the core of the 304 anticline, the La Vida and Yorba members of the Puente Formation are thicker (Figure 6). Both of these members are composed of siltstone and shale and are more susceptible to shearing.

Fault propagation folding

Another possibility is that the 304 anticline is a fault propagation fold. The 304 anticline is northeast verging, suggesting that if it formed by fault propagation, there may be a southwest-dipping blind reverse fault located southwest of the Puente Hills. If so, this may represent a previously unknown seismic source in the northeastern Los Angeles basin.

One of the characteristics of the 304 anticline is that it ends at Turnbull Canyon. The Rideout Heights anticline also ends at Turnbull Canyon. The termination of these folds could be explained if the faults causing these folds both ended at this point. If so, this area, which is also located near the end of the Whittier fault where it turns into the East Montebello fault, could be an earthquake segment boundary as suggested by Huftile (personal comm., 1997). Huftile (1996) described the Montebello anticline located northwest of the study area as a north-verging fold resulting from slip along a south-dipping blind fault. He suggested that the eastern end of the Montebello anticline may terminate against a north-south trending segment boundary, possibly a lateral ramp.

Although the 304 and 184 anticlines could be the result of motion on a blind fault, the fault may be a bedding plane shear fault similar to the faults cutting up along the hinges of the anticlines, in which case the fault may be aseismic. Based on the structural thickening in the core of the folds and the smaller bedding plane shear faulting present in the anticlines, it appears more likely that the 304 and 184 anticlines are a result of bedding plane shear.

Footwall uplift

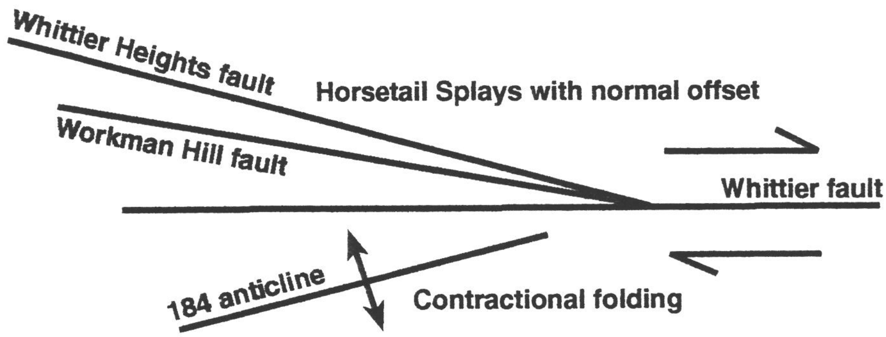
In the Central and La Habra areas of the Whittier oil field, south of Turnbull Canyon, the Whittier fault is within the Puente Hills because of uplift of the footwall of the Whittier fault on the southwest. Footwall uplift in this area can be explained by reactivation of folding of the 184 anticline.

At present, the sense of slip on the Whittier fault is right-lateral strike-slip. This results in a right-lateral wrench zone along the Whittier fault. The 184 anticline trends N75°W, which is about 10-15° counterclockwise from the strike of the Whittier fault in this area. The 184 anticline is within the range of angles that should cause the fold to experience contraction normal to its axis (Figure 12; Wilcox et al., 1973; Harding et al., 1985). The result is reinitiation of folding leading to uplift of the footwall above the fold. Footwall uplift is only present above the 184 anticline. West of Turnbull Canyon, there is no footwall uplift where the strata in the southwest limb of the Rideout Heights anticline are overturned, indicating that these overturned beds are part of an inactive structure.

Footwall uplift can also be explained by the presence of a blind reverse fault. Yeats and Huftile (1995) point to a similar situation in the San Fernando Valley. The Northridge blind thrust, which was responsible for the 1994 Northridge earthquake, caused uplift in the overlying footwall of the Santa Susana fault similar to the footwall uplift in the Puente Hills.

Movement history of the Whittier fault

Except for possible normal offset on the Whittier fault in the middle to late Miocene, at the time of deposition of the Topanga Formation, no clear evidence exists for movement on the Whittier fault in the study area until the late Pliocene. Yeats and Beall (1991) show that there was significant normal offset on the central part of the Whittier fault southeast of the study area based on the deposition of Mohnian Division D and E growth strata northeast of the fault, but their study does not document offset on the northwestern segment at this time.



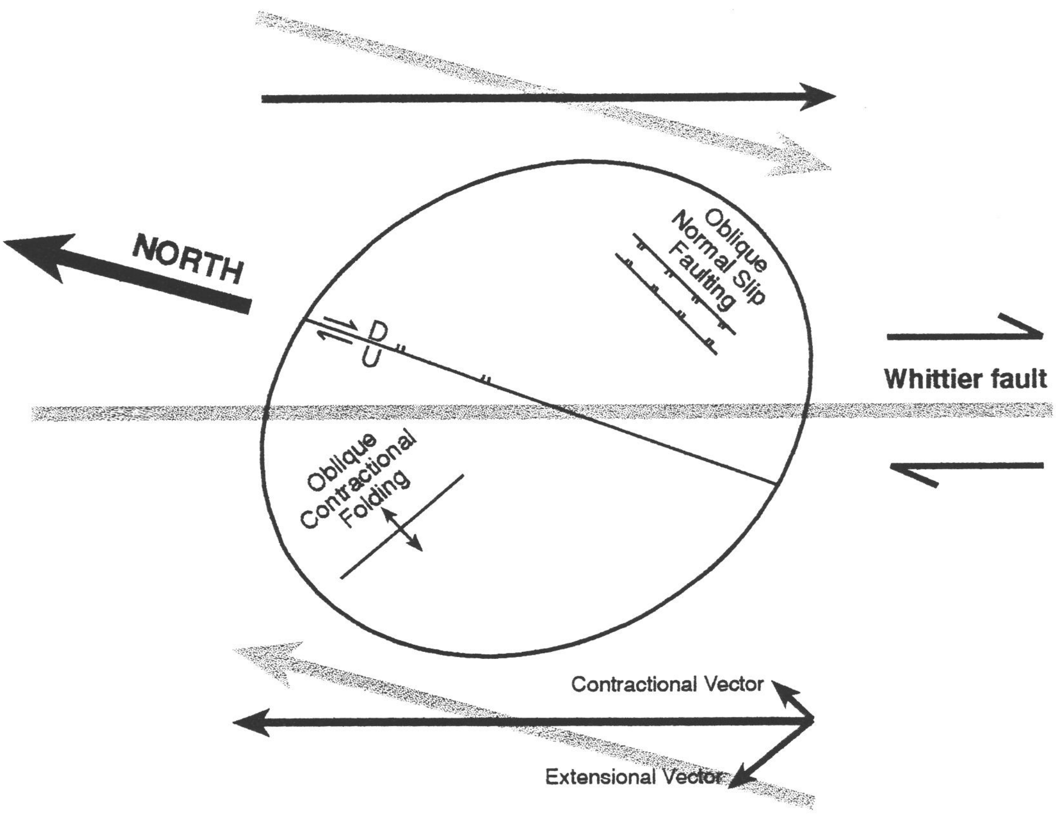


Figure 12 Strain ellipse showing the orientation of structures resulting from right-lateral wrench faulting similar to those located in the northern Puente Hills. The larger gray arrows indicate the present regional principle stress direction relative to the Whittier fault. The structures in the Puente Hills are possibly a result of a secondary stress field about the Whittier fault shown by the black arrows. The upper diagram shows horsetail splays and a contractional fold in similar orientations to the Workman Hill and Whittier Heights faults and 184 anticline (after Harding et al., 1985).

The late Pliocene upper member of the Fernando Formation located southwest of the Whittier fault contains locally derived clasts of the Puente Formation (Yerkes, 1972). The presence of these clasts is evidence for uplift of the hanging wall of the Whittier fault. The clasts were probably eroded from the uplifting hanging wall block, and then deposited on the footwall block. Uplift of the hanging wall block from reverse slip on the Whittier fault at this time corresponds to the period of regional contraction.

Reverse offset on the Whittier fault continued until approximately 2.5 Ma. At that time, a component of right-lateral strike-slip may have been added to the Whittier fault, corresponding with the time of formation of the Elsinore fault (Hull and Nicholson, 1992; Lamar, 1992; Magistrale and Rockwell, 1996). Right-lateral motion on the Whittier fault is used to explain the formation of the Workman Hill and Whittier Heights faults located in the northwestern Puente Hill.

The formation of normal faults in the same orientation as the Workman Hill and Whittier Heights faults is analogous to the formation of horsetail splays during strike-slip wrench faulting (Figure 12; Christie-Blick and Biddle, 1985; Harding et al., 1985). In a wrench-dominated strike-slip system, faults that splay and bend so that the direction of extension is more perpendicular to their strike can have normal offset (Figure 12; Harding et al., 1985). If this is the case, then formation and faulting on the Workman Hill and Whittier Heights faults most likely took place after the Whittier fault began right-lateral strike-slip.

As described above, because of the orientation of the Whittier fault as a large restraining bend in the Elsinore-Whittier-East Montebello fault system, reverse offset and uplift of the hanging wall has continued to the present day. This is evident from the presence of Puente Formation clasts throughout the entire upper member of the Fernando Formation, as well as the overlying La Habra Formation and alluvial deposits located southwest of the Whittier fault (Yerkes, 1972; Gath, 1997).

Quaternary faulting

Motion on the Whittier fault toward the southeastern end has been shown to be nearly pure right-lateral strike-slip, but along the northwestern segment of the Whittier fault there is a component of reverse dip-slip, along with a possible right-slip component that was not determined by this study. The reverse dip-slip rate along the northern part of the Whittier fault is based on the apparent uniform altitude of the Puente Hills, indicating that the uplift rate of 0.57 ± 0.05 mm/yr at its southeastern end (Figure 1) is probably similar along its entire length (Gath, 1997). This suggests that the reverse dip-slip rate on the northwestern Whittier fault is approximately 1.0 ± 0.5 mm/yr, based on the uplift rate and a fault dip of 75°.

Gath (1997) mapped recent fault offsets, possibly strike-slip, along the Whittier fault using aerial photographs to identify geomorphic features associated with faulting. South of Turnbull Canyon, recent offsets are on or near the surface trace of the Whittier fault mapped by Yerkes (1972). North of Turnbull Canyon, recent offsets appear to be within the Puente Hills northeast of the Whittier fault (Figure 13). These offsets may be the result of the Whittier fault attempting to straighten itself by bypassing the restraining bend located at Turnbull Canyon. If the identified geomorphic features are

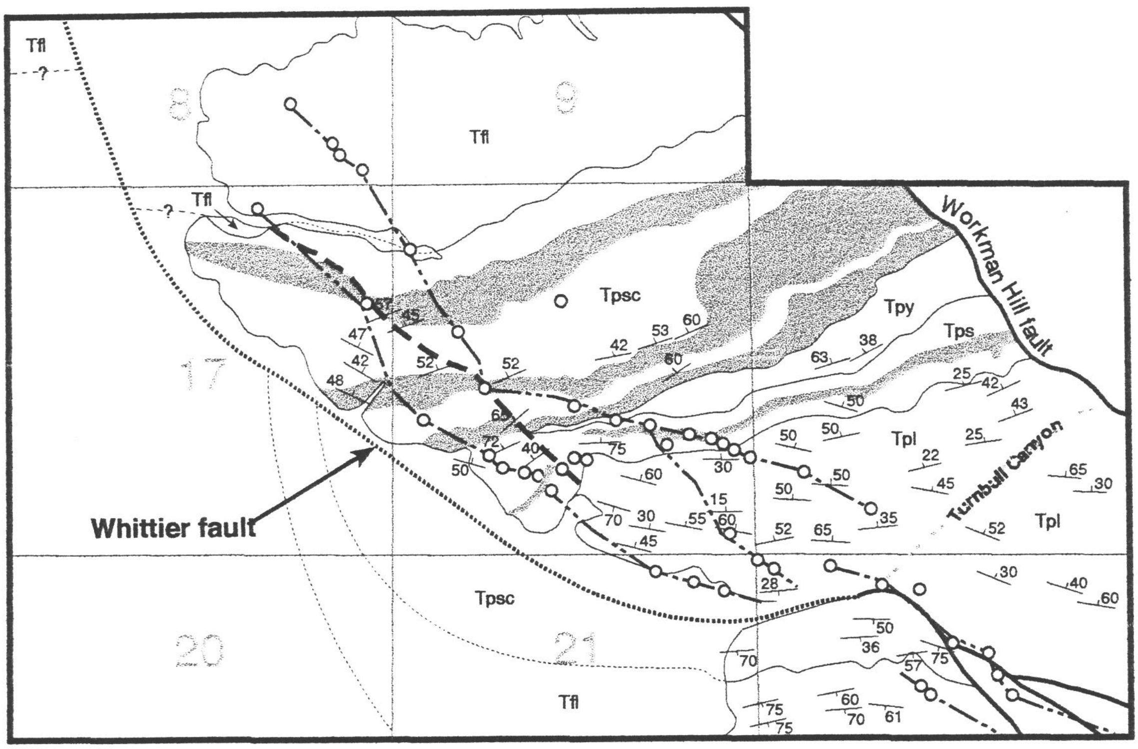


Figure 12 Northwest Puente Hills conglomerates. Shading indicates conglomerate beds mapped by Yerkes (1972), Daviess and Woodford (1949), and Cross (1948). Dashed and dotted lines indicate active fault traces mapped by Gath (1997) based on control points shown by circles. Strike and dip symbols show the general change in strike from east-west to northwest-southeast of strata north of Turnbull Canyon as the strata approach the Whittier fault. Heavy dashed line is fault mapped by Cross (1948). Fault and formation subcrop contacts are dotted. Key to abbreviations: Tfu-upper member Fernando Fm.; Tfl-lower member Fernando Fm.; Tpsc-Sycamore Canyon member, Puente Fm.; Tpy-Yorba member, Puente Fm.; Tps-Soquel member, Puente Fm.; Tpl-La Vida member, Puente Fm.

associated with faulting, this movement is too recent to offset conglomerate beds in the northwestern Puente Hills more than a few tens of meters (Figure 13).

Evidence cited by Gath (1997) for active faulting north of Turnbull Canyon, such as deflected drainages and tonal lineaments, can also be explained by a change in strike of strata approaching the Whittier fault from east-west to northwest-southeast (Figure 13). The change in strike of the strata is due to folding of the Rideout Heights anticline.

Cross (1948), Yerkes (1972), and Daviess and Woodford (1949) have also mapped faults in this part of the northwestern Puente Hills. Some of these faults may be explained by abrupt facies changes within the conglomerate sequence. Many of these faults are short and are not consistent from map to map, except for the longest fault shown in figure 13 as mapped by Cross (1948). This fault does not match up with the recent traces of Gath (1997), and is probably associated with folding of the Rideout Heights anticline, and not recent strike-slip. Normal faults similar to these faults are common in the shallower limbs of folds (Jaroszewski, 1984, p. 487), such as the northeast limb of the Rideout Heights anticline.

Shortening across Rideout Heights anticline

Figure 14 shows a cross section through the Rideout Heights anticline from the La Habra to San Gabriel synclines. The shortening calculation is based on measurements taken from pin lines at the axis of both synclines. It is assumed that no layer parallel slip occurred through these pin lines (see discussion of this problem by Schneider, 1994). The top of the Puente Formation and the top of the lower member of the Fernando Formation (top

Repettian stage) are projected into the air based on surface dips, and by assuming that the Rideout Heights anticline is balanced (matching hanging wall and footwall cutoff angles) with minimal strike slip on this part of the Whittier fault (Figure 13). The location of the La Habra synclinal axis is from Yerkes (1972) and Wright (1991). The poorly-constrained location of the San Gabriel synclinal axis is from Wright (1991).

As shown in Figure 14, the shortening of the top of the Puente Formation and the top of the lower member of the Fernando Formation are nearly the same. Although there is some growth of strata toward the synclinal axes and there was some broad folding of the Rideout Heights anticline during the deposition of the lower member of the Fernando Formation, it is assumed that at the end of deposition of the lower member the upper surface was nearly flat, and most of the shortening occurred after that time. For that reason the shortening calculation is based on the top of the lower member of the Fernando Formation, which is approximately 2.5 Ma according to Blake (1991). The shortening rate is approximately 1.0 mm/yr. If shortening began later, after the deposition of the younger member of the Fernando Formation the shortening rate would be higher. On the other hand, if the top of the lower member is time-transgressive, older at Whittier Narrows than it is in the Repetto Hills in the Los Angeles basin to the west, the shortening rate would be lower. Accordingly, I assume an error of ±0.5 mm/yr in convergence rate.

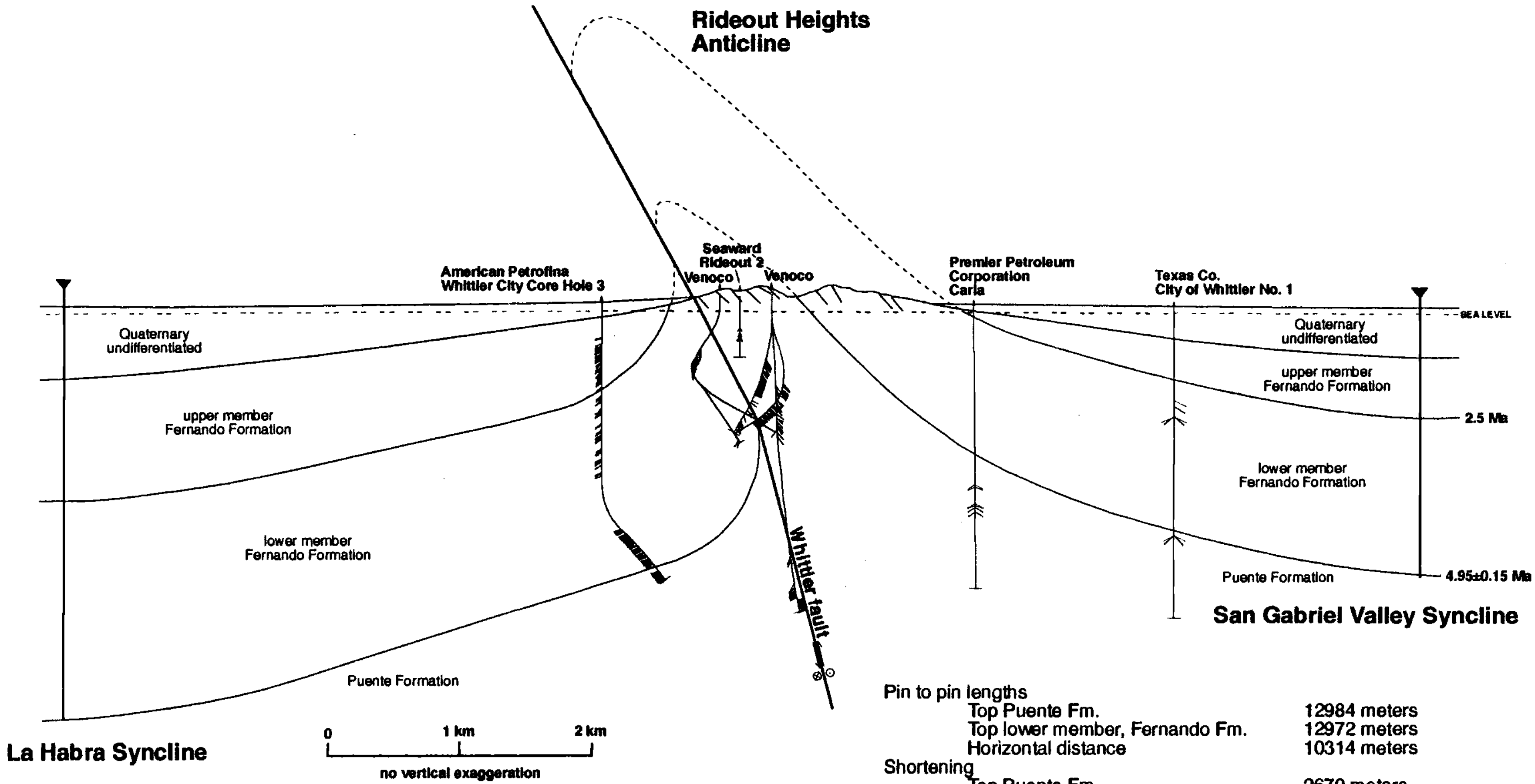
Earthquake hazard of the northwestern Whittier fault

To understand the earthquake hazard in the northwestern Puente Hills several problems need to be considered. If the Puente Hills are uplifting uniformly along their length, then the reverse slip rate component for the northern part of the Whittier fault is approximately 1.0 mm/yr. There is a possible component of strike-slip offset along this part of the Whittier fault that was not determined by this study, but needs to be taken into consideration when determining the earthquake hazard.

Segment boundaries where the Whittier fault turns from the west-northwest to the northwest into the East Montebello fault and possibly at Turnbull Canyon may affect how slip propagates along the fault zone. Whether slip on the fault is hindered by or transferred between these boundaries would relate to the size of earthquakes characteristic to this part of the fault.

If the northeast verging 304 anticline is related to a southwest dipping blind thick-skinned reverse fault, then this fault may be a possible seismic source, one that was previously unknown in this part of the Los Angeles basin. However, the low angle of the fault with respect to bedding at depth suggests that this fault is a product of bedding-plane shear folding and is not a separate seismic source.

An earthquake hazard prediction for the Whittier fault needs to account for faulting occurring on only a single segment, or on multiple segments, as well as possible faulting on all sources in the area during a single large earthquake. Resolution of this problem depends on future paleoseismological studies.



Pin to pin lengths	
Top Puente Fm.	12984 meters
Top lower member, Fernando Fm.	12972 meters
Horizontal distance	10314 meters
Shortening	
Top Puente Fm.	2670 meters
Top lower member, Fernando Fm.	2658 meters
Rate based on top lower member Fernando Fm.	1.06 mm/yr

Figure 14 Calculation of shortening across the Rideout Heights anticline. Central part of diagram from cross section A-A' (Figure 4). Formation boundary ages from Blake (1991). The top of the upper member Fernando Formation is poorly constrained.

CONCLUSION

The Whittier fault in the northwestern Puente Hills dips 70-75° northeast. It is located near the Puente Hills range front north of Turnbull Canyon. South of Turnbull Canyon the Whittier fault is located in the Puente Hills due to footwall uplift. There are two possible explanations for this: reactivation of the 184 anticline caused by strike-slip wrench faulting, or by reverse offset on a blind fault located in the footwall, both of which could cause footwall uplift.

The Whittier fault may have had apparent normal offset in the middle Miocene, but most likely had little if any offset on the northwestern part of the fault until the Pliocene. Clasts of reworked Miocene Puente Formation strata from the hanging wall is found throughout the late Pliocene Fernando Formation strata in the footwall indicating reverse offset on the Whittier fault at that time. The present sense of slip on the southeastern part of the Whittier fault is nearly pure right-lateral strike-slip at rate of 2-3 mm/yr, but the northwestern part has a component of reverse offset at a rate of approximately 1.0 mm/yr, and most likely has a component of right-lateral strike-slip.

In the late Miocene and early Pliocene, three low-amplitude anticlines formed in the Whittier oil field area of the Puente Hills. The Rideout Heights anticline that trends northwesterly from the mouth of Turnbull Canyon through Rideout Heights appears to have formed as a basement-involved compression fault propagation fold. The 304 and 184 anticlines located in the footwall block in the Central and La Habra areas of the Whittier oil field appear to have formed as bedding plane shear folds in the northeastern limb of the La Habra syncline, but could have also formed by faulting on a blind reverse fault located to the southwest of the Whittier fault.

The earthquake hazard present on the northwestern part of the Whittier fault can be influenced by several factors. Both the reverse slip rate of approximately 1.0 mm/yr and an unknown strike-slip rate on the fault need to be considered. The possibility of fault segmentation along with the presence of a previously unknown blind reverse fault influence the way fault movement may propagate through the area and the total amount of energy released during an event. Current earthquake hazard predictions for the Whittier fault are based on evidence mainly from the southeastern part of the fault. The information presented in this paper along with data from future studies may help to better characterize the fault, which will lead to a more accurate prediction of the earthquake hazard present along the Whittier fault.

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