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Cenozoic Structure of the Piru 7½-minute Quadrangle, California

by

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ABSTRACT

The Piru 7½-minute quadrangle in the central Ventura basin contains a thick accumulation of Plio-Pleistocene sedimentary rocks bordered by opposing reverse faults, on the north by the north-dipping San Cayetano fault and on the south by the south-dipping Oak Ridge fault. Deformation in the Piru quadrangle can be separated into three phases: (1) pre-Vaqueros (late Oligocene-early Miocene) tilting in the hanging-wall block of the Oak Ridge fault that is coincident with normal faulting farther south at Big Mountain, (2) pre-Pleistocene reverse faulting of the Torrey fault, and (3) Quaternary deformation. Strands of the San Cayetano and Oak Ridge faults offset late Quaternary surfaces. East of Sespe Creek, the San Cayetano fault has a lobate surface trace, and the dip of the fault shallows to as much as 27°N. Farther east, the fault bifurcates into two strands; the northern, Main strand trends northeast, cuts an alluvial fan 2½ km ENE of Piru, and dies out; the southern, Piru strand trends east and dies out near the eastern boundary of the quadrangle. The Oak Ridge fault has variable, low dips in its upper 2.5 km to the west and is more steeply dipping to the east where it bifurcates into three strands and dies out south of the eastern terminus of the San Cayetano fault. Near the eastern termini of the San Cayetano and Oak Ridge faults, displacement is taken up on east-trending folds and south-dipping reverse faults of the East Ventura fold belt.

INTRODUCTION

The Piru quadrangle is located in the central Ventura basin, part of the western Transverse Ranges of southern California. The Ventura basin contains the world's thickest sequence of Pleistocene age strata (Yeats, 1977), found in the subsurface in the Santa Clara Valley in the southwestern corner of the quadrangle (Figure 1, Plate 1A). This sequence is folded in the Santa Clara syncline and is bounded on the north by the San Cayetano reverse fault and on the south by the Oak Ridge reverse fault (Figure 1). The surface traces of these two reverse faults are only about 1 km apart in the southwestern part of the quadrangle, but at depth, the area between the faults is more than 10 km wide.

On the south side of the Santa Clara Valley, the hanging-wall block of the Oak Ridge fault contains strata as old as Oligocene at the surface. Farther east, the Oak Ridge fault divides into three strands (Figure 1, Plate 1A), and only the northern strand at the edge of the Santa Clara Valley appears to be active. In the subsurface of the hanging-wall block of the Oak Ridge fault, wells penetrate strata as old as Paleocene (Seedorf, 1983). On the north side of the Santa Clara Valley, the Modelo lobe (Figure 1) of the San Cayetano fault consists of a fold belt of Miocene strata with fold axes parallel to the southward-convex surface trace of the fault. One well reaches Oligocene strata, and Oligocene and Eocene strata are exposed west and north of the quadrangle.

In the eastern part of the quadrangle, the San Cayetano fault bifurcates into the Main strand along the lower part of Piru Creek and the Piru strand at the northern edge of the Santa Clara Valley (Figure 1, Plates 1A and 3A). Both strands cut late Quaternary deposits. Both the San Cayetano and Oak Ridge faults lose separation eastward as they bifurcate. The Main strand of the San Cayetano fault dies out in Piru Creek, and the other strands of both faults die out near the eastern boundary of the quadrangle. The folds of the Modelo lobe continue eastward across Piru Creek and form part of the East Ventura fold belt (Figure 1). The western ends of the south-dipping Holser and Del Valle faults can be traced to Piru Creek, but cannot be found west of the creek. These faults increase separation eastward.

The geologic map (Plate 1A) was compiled (Figure 2) from Çemen (1977), Ricketts and Whaley (1975), Rieser (1976), Morton (1972), Argo Petroleum (1982), Dibblee (1991), and from unpublished maps by T. L. Bailey (1951) and J. C. Crowell (1953). Other maps consulted but not used extensively in the compilation include California Division of Mines and Geology (1972), an unpublished map by G. J. Welsh (1972), and University of California at Los Angeles masters theses by Bain (1954), Cordova (1956), Robinson (1956), and Jestes (1957). Dibblee (1991) published a geologic map of the Piru quadrangle, but did not consider the subsurface. Because of our interpretation of the subsurface, we disagree with several areas of Dibblee's surface map, particularly the trends of the Oak Ridge fault and the Buckhorn anticline.

The present study began with surface and subsurface mapping by Ricketts and Whaley (1975) of the Oak Ridge fault set east of Wiley Canyon (Plate 1A), Rieser (1976) of the Oak Ridge fault west of Wiley Canyon, and Çemen (1977) of the Modelo lobe of the San Cayetano fault. Further work was done by Stitt and Yeats (1983) north of the Santa Clara Valley and by Huftile in the Piru Creek area and south of the Oak Ridge fault in the Wiley Canyon and Torrey Canyon area. Open-file maps, including subsurface cross sections, of the Val Verde and Whitaker Peak quadrangles east of the Piru quadrangle were published by Yeats et al. (1985); the present report follows the same format.

Data were collected from wells drilled by the petroleum industry (Plate 1B). Well data, provided by the California Division of Oil and Gas and by various petroleum companies, include electric logs, core descriptions, mud logs, dipmeter logs, directional surveys, and paleontological reports. Paleontologic data were used without reexamining the fossils ourselves or reevaluating the biostratigraphic correlations. Critical areas had to be remapped entirely (Huftile 1988a, b; and previously unpublished mapping along Piru Creek and Piru Lake; Figure 2), while others required only minor revisions. We concentrated on Quaternary structural relations. Cross sections were compiled from Çemen (1977), Ricketts and Whaley

(1975), Rieser (1976), Huftile (1988 a, b), and L. T. Stitt (unpublished cross sections) drawn with electric logs at larger scales, reduced to 1:24,000 (map scale) and redrafted without electric logs on Plate 2.

This paper is part of a larger effort to calculate crustal convergence rates across the Ventura basin through the balancing and retrodeforming of cross sections. Balancing cross sections requires detailed knowledge of the geology and the timing of structures. Thus, we have found it necessary to do detailed studies of areas in preparation for drawing a balanced cross section. This is one of those studies, as is Huftile (1991) and Yeats et al. (1994).

STRATIGRAPHY

Basement rocks are not observed in the Piru quadrangle. To the northeast, in Whitaker Peak quadrangle (Figure 1), basement is composed of Precambrian gneiss and Mesozoic granodiorite (Yeats et al., 1985). There, basement is overlain by unnamed Eocene strata (Squires, 1981) that are not observed in the subsurface of Piru quadrangle. South of the Oak Ridge fault, the Eocene Llajas Formation as well as underlying Paleocene or Cretaceous strata are penetrated by wells just south of the quadrangle boundary (Ricketts and Whaley, 1975; Seedorf, 1983; Yeats, 1988b). Late Eocene to early Miocene nonmarine Sespe Formation and the lower Miocene shallow marine Vaqueros Formation form the top of a sandstone-rich, competent sequence. The early Miocene Rincon Formation is composed of deep-water mudstone and siltstone that are less competent than the underlying strata. The Rincon Formation is not found south of the Oak Ridge fault. The middle Miocene to lower Pliocene Modelo and Towsley formations comprise part of a submarine fan system deposited in deep water, becoming shallower water upsection (cf. Winterer and Durham, 1962). The Pliocene Fernando Formation was deposited as turbidites transported down the axis of the Santa Clara syncline. Water depths continued to shallow upsection through deposition of the Pleistocene Saugus Formation which is nonmarine in its upper part.

Llajas Formation (Tll). The Eocene Llajas Formation is observed in the subsurface to be interbedded gray, fine- to medium-grained, silty sandstone and dark gray silty sandstone. The Texaco Shiells 165 well (Plate 1B; Plate 2, A-A') penetrated 721 m (Rieser, 1976); in the Union Torrey 92 well, 548 m of Llajas was penetrated. Mallory (1959) and Schmidt (1970) placed the formation in the Penutian and Ulatisian (middle Eocene) stages. Canter (1974) listed benthic foraminifera of the Ulatisian Stage from Big Mountain to the south (Figure 1). At its type locality in the Simi Hills, Squires (1981) noted foraminifera of the late Eocene Narizian Stage near the top of the formation.

Sespe Formation (Tsp). The Sespe Formation is composed of nonmarine sandstone, siltstone and conglomerate. Generally, red sandstone and conglomerate characteristic of the type section at Sespe Creek (Figure 1), west of the quadrangle, are absent on Oak Ridge, and the maroon and green silty claystone and greenish gray sandstone characteristic of the Oak Ridge section is not found at the type locality. Correlation of vertebrate fossils to benthic foraminifera stages yielded ages of late Eocene (Uintan Stage) to early Miocene (Arikareean Stage; Stock, 1932; Wilson, 1949; Savage et al., 1954; Durham et al., 1954; Mason and Swisher, 1988). Berggren and Van Couvering (1973) suggested that the Sespe Formation is Refugian and Zemorrian. More recently, Lander (1983) used vertebrate fauna to conclude a range of late middle or late Eocene to late Oligocene for the Sespe.

The Sespe Formation crops out in the cores of anticlines, in the hanging-wall block of the Oak Ridge fault, in the southwestern part of the quadrangle. The Sespe Formation is composed of variegated fine- to very coarse-grained, silty sandstone that is occasionally massive, interbedded with maroon to dark green sandy claystone, red to white to green siltstone and claystone, and red to gray, thin-bedded, sandy siltstone (Ricketts and Whaley, 1975).

Thicknesses south of the Oak Ridge fault range from 1860 m in the southwest corner of the quadrangle (Rieser, 1976), to 1830 m in the Oxy Davis-USL 83X-1 well just south of cross section B-B'

(Plates 1B and 2), to greater than 2100 m in the Texas Hunter 1 well just south of cross section D-D'.

North of the San Cayetano fault, the Sespe Formation is unexposed in the Piru quadrangle. To the west, in the type section along the lower Sespe Creek (Figure 1), Eschner (1957) reported 853 m of exposed section. Wells in the Sespe field produce from the Sespe Formation. Down plunge, the Union Moran 1 (Plate 1B; Plate 2, A-A') well is the easternmost well in Piru quadrangle and north of the San Cayetano fault to reach the Sespe Formation; it penetrated 15 m of maroon, massive, hard, fine- to medium-grained sandstone interbedded with maroon to red sandy shale and greenish-gray, thin-bedded, sandy siltstone.

To the northeast, in Whitaker Peak quadrangle, Bohannon (1976) observed 700 m of Sespe Formation at Canton Canyon. Yeats et al. (1985) divided the formation into two members, a basal conglomerate and breccia member overlain by a red-brown sandstone and red mudstone member.

North of Piru quadrangle, in Cobblestone Mountain quadrangle, J. C. Crowell (1953, unpublished mapping) shows approximately 150 m of the sandstone member.

Vaqueros Formation (Tv). The Vaqueros Formation is composed of transgressive marine sandstone and siltstone deposited in shallow-water (Edwards, 1971; Jestes, 1957). Its age was considered by Edwards (1971) to be Zemorrian. Canter (1974) found evidence for the formation at Big Mountain, to the south (Figure 1), to be, in part, Saucesian; Blake (1983) determined that only the lowermost part of the formation is latest Zemorrian to early Saucesian and that the overlying strata are early Saucesian neritic equivalents to the overlying, bathyal Rincon Formation.

The Vaqueros is exposed south of the Oak Ridge fault and west of Torrey Canyon (Plate 1A). It was shown by Jestes (1957) to be 472 m thick at Wiley Canyon, and by Ricketts and Whaley (1975) to be 305-396 m thick in Torrey Canyon. The formation thins to the east because of pre-middle Miocene erosion. It is composed of gray to brown, fine-grained, massive to thin-bedded sandstone interbedded with tan to light gray sandy siltstone (Ricketts and Whaley, 1975). It is distinguished from the underlying Sespe Formation by the presence of megafossils. Hall et al. (1967) and Canter (1974) show that the contact with the underlying Sespe Formation is unconformable at Big Mountain (Figure 1) as does Huftile (1988a, b) at Wiley Canyon.

North of the San Cayetano fault, the Vaqueros Formation is exposed just west of the northwest corner of the Piru quadrangle (Dibblee, 1990; Eschner, 1957; Edwards, 1971; Çemen, 1977, 1989; Argo Petroleum, 1982) and to the northeast of the quadrangle (J. C. Crowell, 1953, unpublished mapping; Yeats et al., 1985). Edwards measured 165 m of Vaqueros along Little Sespe Creek (Figure 1). North and northeast of Piru quadrangle, Crowell (1953, unpublished mapping) mapped a 110 m thick section and Edwards (1971) measured an 80 m section along Piru Creek, The Union Moran 1 well (Plate 1B) penetrated 83 m of greenish gray, massive, medium- to fine-grained sandstone.

Rincon Formation (Tr). The Rincon Formation is not found south of the Oak Ridge fault and Miocene strata are not penetrated in the footwall block of the Oak Ridge fault. The Rincon Formation is exposed in the northwest corner of the Piru quadrangle along Tar Creek (Plate 1A). The Union Moran 1 well penetrated 732 m (Plate 1A, A-A'; Plate 1B) of massive, gray to black, hard, dense, brittle siltstone and mudstone. Eschner (1957) measured 275 m of bluish-black mudstone and shale to the west, along Little Sespe Creek (Figure 1). To the north of Piru quadrangle, along Piru Creek, Edwards (1971) found 280 m of section that was predominantly mudstone. Eschner (1957) determined its age to be late Zemorrian to Saucesian (early Miocene).

Modelo Formation (Tm). The type section, first described by Eldridge and Arnold (1907), is in Modelo Canyon, west of Piru Creek. Kew (1924) identified five members, the upper shale, upper sandstone, middle shale, lower sandstone, and lower shale although he included the Rincon Formation and part of the Vaqueros Formation in his lower shale member and the Towsley Formation in his upper member. The Modelo Formation ranges in age from Relizian through Mohnian (middle and upper Miocene). The formation was deposited by turbidity currents in bathyal water depths (Natland and Kuenen, 1951; Berger, 1977).

The Modelo Formation is exposed between the north and south strands of the Oak Ridge fault (Plate 1A). There the Modelo ranges in age from Luisian to Mohnian (Ricketts and Whaley, 1975), and it unconformably overlies the Vaqueros Formation. Ricketts and Whaley (1975) divided the formation south of the Oak Ridge fault into three members: (1) the basal member is Luisian and is composed of gray to grayish tan to brown, predominantly fine- to very fine-grained, soft, friable sandstone interbedded with gray to tan to brown, fossiliferous, sandy siltstone and shale (Tmss) overlain by light brown to gray to black, fossiliferous, silty shale interbedded with grayish tan to brown, fossiliferous, sandy siltstone (Tmsh); (2) the middle member (Tmd) is lower Mohnian in age and is composed of white to light brown, siliceous shale, dark brown diatomaceous shale, and tan to gray, impure chert; and (3) the upper member (Tms) is upper Mohnian in age and is composed of interbedded light brown siliceous siltstone, dark brown diatomaceous siltstone, and light reddish brown chert. Cross sections A-A', B-B', and C-C' (Plate 2) show a sliver of Modelo Formation wedged into the fault zone of the Oak Ridge fault.

North of the San Cayetano fault, Kew (1924) defined five members of the Modelo Formation, all of which are exposed in the Modelo lobe area (Figure 1). The lower shale member (Tm1) is penetrated by the Getty Temescal 14, McCulloch Hopper Canyon 1, McCulloch Hopper Canyon 1A, and Pacific Western Crocker Fee 1-D wells (Plate 1B; Plate 2, E-E', F-F', A-A, and D-D'). It is Relizian to Luisian in age (Çemen, 1977) and is composed of dark gray to brown to black, massive, hard, fractured shale interbedded with light gray, medium- to coarse-grained sandstone. The Union Moran 1 well penetrated 794 m of the lower shale member. In the northwest corner of the quadrangle, the contact between the Rincon Formation and the overlying lower shale member of the Modelo Formation is convex to the east; the overlying contact between the lower shale and lower sandstone members of the Modelo is highly deformed (Plate 1A), implying that the décollement beneath the Modelo lobe is in the lower shale member of the Modelo Formation.

The overlying lower sandstone member (Tm2) is penetrated by several wells (Plate 2, A-A', D-D', E-E, and F-F') and it is Luisian in age (Çemen, 1977). It is composed of white-gray to dark brown, fine- to medium-grained sandstone interbedded with dark brown, massive siltstone and claystone. Its thickness varies from 550 m to 1005 m; it is about 700 m thick in the McCulloch IDS 1-16 and Getty Temescal 14 wells.

The middle shale member (Tm3) is lower Mohnian in age (Eschner, 1957; Çemen, 1977). In the subsurface, it ranges from 152 m to 640 m thick (Plate 2). The middle shale is composed of dark brown, hard, cherty, porcelaneous and calcareous shale.

The upper sandstone member (Tm4) varies in thickness between 275 m at the surface north of Piru and 825 m at the surface near Temescal anticline (Cordova, 1956); in the subsurface, McCulloch IDS 1-16 penetrated a complete section, 640 m thick. It is composed of white to gray. thick- to thin-bedded, fine- to coarse-grained arkosic sandstone interbedded with subordinate amounts of siliceous and silty clay shale (Çemen, 1977). Truex (1977) correlated this member with the lower Mohnian.

The upper shale member (Tm5) was correlated by Kleinpell (1938) as upper Mohnian to lower Delmontian in age along outcrops in Modelo Canyon. At the surface, the upper shale member is 200 m thick in Santa Felicia syncline to 488 m thick east of Piru Creek. Dibblee (1991) maps this member as Sisquoc Formation, which is Delmontian to the west. However, Mohnian benthic foraminifera are found throughout this member and in the overlying Towsley Formation in the Arco Black Ranch 7-15 and Arco Hamilton Brothers Black Ranch 12-84 wells to the east in Val Verde quadrangle (Yeats et al., 1985). The authors believe that there is sufficient reason to continue calling this section the upper shale member of the Modelo Formation.

Towsley Formation (Tt). Coarse-grained sandstone strata deposited in deep water by turbidity currents and overlying the Modelo were named by Winterer and Durham (1954) the Towsley Formation. Winterer and Durham (1962) reported late Miocene to early Pliocene fauna. The lower part of the Towsley contains Mohnian foraminifera and the upper part is Delmontian; ***Rotalia miocenica,*** one of the key foraminifera used in establishing the Delmontian Stage at Oak Ridge, was found in the Oceanic Marr-Sloan 1 well (Ricketts and Whaley, 1975), in the southwest corner of the Val Verde quadrangle (Figure 1).

South of the Santa Clara River, Towsley Formation is exposed between the middle and north strands of the Oak Ridge fault. There, Ricketts and Whaley (1975) divided the formation into two members based on lithology: The lower member (Tts) is composed of tan, coarse-grained, poorly sorted, massive sandstone interbedded with chocolate brown, foraminiferal siltstone; the upper member (Ttu) is composed of tan, sandy siltstone interbedded with chocolate brown siltstone and red to white, iron-stained, coarse-grained, pebbly, indurated sandstone lenses (Ricketts and Whaley, 1975). Thickness ranges from 1097 m to 1433 m (Plate 2, E-E', F-F').

Two wells penetrate the upper part of the Towsley in the footwall block of the Oak Ridge fault (Plate 2, E-E'). The Shell Sloan 1 well penetrated 282 m of gray to black, hard, massive siltstone interbedded with light brown, fine- to medium-grained sandstone and light gray to gray-brown conglomerate overlain by a conglomerate bed, 78 m thick.

North of the San Cayetano fault, the Towsley was divided into four members by Çemen (1977). The basal conglomerate member is called the Hasley conglomerate (Tthc) by the oil industry. It is composed of reddish-brown, fine-to coarse-grained, pebble- to boulder-conglomerate with clasts of igneous rock. The lower siltstone member (Tts) is composed of light brown to dark greenish brown, thin-bedded siltstone. The upper conglomerate member (Ttc) is composed of white to light gray to reddish brown, thin- to thick-bedded conglomerate interbedded with fine-grained, pebbly sandstone and siltstone. The upper siltstone member (Tts) is composed of siltstone interbedded with white sandstone. Thickness of the Towsley Formation ranges from 378 m just north of the Holser fault to 747 m south of the Holser fault.

Fernando Formation. Fernando Formation is used for middle Pliocene to lower Pleistocene deep-water clastic sedimentary rocks deposited from the east by turbidity currents (Hsü, 1977; Hsü et al., 1980). The strata were described by Eldridge and Arnold (1907) and named by Kew (1924) the Fernando Group which included the Repetto, Pico, Santa Barbara, and Saugus formations. Bain (1954), Cordova (1956), Robinson (1956), Eschner (1957), Jestes (1957), Crowell et al. (1966), Yeats et al. (1985) include the Pliocene rocks in the Pico Formation. Jennings and Strand (1969) reduced the Fernando Group to formation status with the Repetto, Pico, and Santa Barbara members overlain by the Saugus Formation; this terminology was used by Ricketts and Whaley (1975), Rieser (1976), Rockwell (1988), Yeats (1988a, b), and Huftile (1991), and is repeated here. The Santa Barbara member is equivalent to the Mudpit Shale of Nagle and Parker (1971); although it is not observed in the Piru quadrangle. The Repetto member (Tfr) corresponds to the Repettian Stage of Natland and Rothwell (1954). It is exposed in the eastern part of the Piru quadrangle on both sides of the Santa Clara syncline, in the hanging-wall blocks of the Piru strand of the San Cayetano fault and of the Camulos fault-north strand of the Oak Ridge fault. It is composed of green to tan siltstone interbedded with tan, lenticular sandstone and conglomerate (Ricketts and Whaley, 1975; Çemen, 1977). It is about 734 m thick, determined from surface outcrops and well data, about 2.5 km east of Piru quadrangle (Çemen, 1977); along cross sections E-E' and F-F' (Plate 2), the thickness is about 730 m.

The Pico member (QTf) contains microfossils referred to the Venturian and lower Wheelerian stages of Natland and Rothwell (1954). Blackie and Yeats (1976) showed that the Olduvai normal event, near the Plio-Pleistocene boundary at 1.6-1.8 Ma, is within the Pico member at Saticoy oil field, ~10 miles west of Piru quadrangle, however, the boundary is time-transgressive. Thus, the Pico member is Plio-Pleistocene. Winterer and Durham (1962) reported a trend from deep-water faunas near the base of the Pico to shallow-water faunas near the top. Pico strata crop out in the footwall block of the Oak Ridge fault and between the Main and Piru strands of the San Cayetano fault (Plate 1A). The Pico is composed of interbedded tan to buff to brown, phosphatic, fine- to medium-grained sandstone, silty sandstone, and olive-green to tan to brown, thin-bedded, friable, glauconitic, sandy siltstone and siltstone. Lenses of brown to tan, medium- to coarse-grained sandstone and brown to white cobble-conglomerate are common. Conglomerates contain clasts of crystalline rocks derived from the San Gabriel Mountains to the east (Jestes, 1957; Hsü, 1977; Hsü et al., 1980). The Texaco Lawton 1 well (Plate 1B, Plate 2, A-A') penetrates 1630 m of Pico without reaching the Repetto member. Farther east, cross sections E-E' and F-F' (Plate 2) constrain the Pico member to be 1890 m thick.

Saugus Formation (Qs). The Saugus Formation appears to overlie the Pico member of the Fernando Formation conformably in the western part of the Piru quadrangle (Plate 2, A-A' through D-D'). Just east of Piru quadrangle, in Val Verde quadrangle, Yeats et al. (1985) show that the contact at the base of the Saugus is an angular unconformity; and east of there, the Saugus pinches out. The Saugus Formation is informally divided into two members, a basal marine member (Qsm) and a nonmarine member (Qsnm) equivalent to the Sunshine Ranch member of Winterer and Durham (1962). Based on a magnetostratigraphic section in the East Ventura basin, east of the Piru quadrangle, Levi and Yeats (1993) estimate the base of the Saugus Formation to be 2.3 Ma and the top of the Saugus to be ~0.5 Ma. To the west, near Ventura, the Saugus Formation has been dated by tephrachronology and amino-acid stereochemistry as between 0.63 and 0.4-0.2 Ma (Lajoie et al., 1982; Sarna-Wojcicki et al., 1984; K. R. Lajoie, written communication to R. S. Yeats, 1988). The base of the Saugus Formation in cross sections A-A' and B-B' (Plate 2) corresponds to foraminiferal horizon 5, shown by Yeats (1981) to be ~1 Ma.

The lower marine member is composed of greenish gray-white to gray, fine- to medium-grained, locally conglomeratic and silty sandstone, greenish gray, soft siltstone and sandy siltstone, and gray and white, coarse-grained conglomerate (Çemen, 1977). In the subsurface of the Santa Clara Valley, the marine member varies in thickness between 427 m in the east and 960 m in the west.

The overlying nonmarine member is composed of light to dark gray, medium- to very fine-grained, firm, massive sandstone and silty sandstone, brown to light gray, friable, fine- to coarse-grained pebble- and cobble-conglomerate. In the subsurface, it ranges from 2926 m thick in the west at A-A' (Plate 2), to 1950 m thick at D-D'; farther east the section is faulted and incomplete.

Alluvial fan material (Qaf). Poorly consolidated to unconsolidated sand and gravel with soil developed at the surface. The fan at the mouth of Modelo Canyon contains abundant platy chips of Modelo Formation.

Terrace material (Qt). Reddish brown, poorly bedded, poorly consolidated gravel, sand, and silt. Terrace surfaces are preserved above present drainage, and terrace deposits rest with angular unconformity on underlying formations.

Landslide material (Qls). Landslides are common throughout the quadrangle with fine-grained Modelo Formation especially susceptible to sliding.

Modern alluvium (Qal). Unconsolidated gravel, sand, and silt with poorly developed soils.

STRUCTURE

The late Quaternary structure of the Piru quadrangle includes the east ends of the Oak Ridge and San Cayetano faults and the west end of the East Ventura fold belt with its south-dipping faults that extend down into bedding. Discussion of structures is divided into five groups: (1) the San Cayetano fault strands, (2) the Oak Ridge fault strands and related folds in its hanging-wall block, (3) the folding of the Modelo lobe and east Ventura fold belt, (4) the Santa Clara syncline, and (5) older faults.

San Cayetano fault. The Piru quadrangle covers the eastern half of the Modelo lobe and the eastern end of the San Cayetano fault (Figure 1). Near Hopper Canyon (Plate 1A), the fault bifurcates into two strands. In the lobate part of the fault, the dip on the fault is 22-34°N at the western edge of the Piru quadrangle; the Main strand dips 40°N just east of the intersection between the Main and Piru strands and as much as 66°NW at its eastern end; the Piru strand has a low dip at its western end and steepens to 54°N at its eastern terminus (Plate 3A). Çemen (1977, 1989) estimated 5.2-7.3 km stratigraphic separation at Hopper Canyon, and 4.6-5.3 km at Edwards Canyon (Plate 1A).

Both strands of the San Cayetano fault have evidence of late Quaternary displacement. On the north, the Main strand of Çemen (1977) trends roughly east-northeast and turns more northerly on the west side of Piru Canyon where it dies out. Across Piru Canyon, older strata exposed on the west are juxtaposed against younger strata on the east, suggesting a component of left-lateral movement on the eastern end of the fault strand. North of Holser syncline, there is no apparent offset of formation contacts, suggesting the fault strand dies out near the Holser syncline. The fan at the mouth of Modelo Canyon (Plate 1A) appears to be cut by the Main strand. Aerial photographs show that drainages are more incised west of the fault than they are east of the fault, suggesting uplift west of the Main strand. Offset of the drainages increases to the south where dip-slip offset should be greater. Some drainages appear to be offset left-laterally, implying oblique offset for this part of the fault as would be expected for a reverse fault that turns in the direction of stress shown by Mount and Suppe (1987) and dies out.

The southern, Piru strand of Çemen (1977) extends to the east through Piru and north of Camulos (Plate 1A). The surface trace can be followed by a warp in alluvium that extends through the town of Piru. The easternmost well that penetrates the strand is the Gulf Rubel 1 well (Plate 1B).

Oak Ridge fault and related structures. The Oak Ridge fault is a post-Saugus, steeply south-dipping fault that forms the southern boundary of the central Ventura basin. Yeats (1988a, b) divided the fault into five segments: (1) the western coastal and offshore segment that does not offset the Pleistocene Saugus Formation, (2) the Saticoy to Santa Paula segment that trends roughly N40°E and has oblique slip because of its trend, (3) the Santa Paula to Balcom Canyon segment which has a steeply south-dipping fault and dip-slip displacement, (4) the Balcom Canyon to Wiley Canyon (Plate 1A) segment which has a lobate surface trace, has shallow dips in the upper 2 km of the fault surface, and has dip-slip displacement, and (5) the eastern segment that separates into three splays and dies out (Figure 1). The Piru quadrangle covers parts of segments 4 and 5 (Figure 1, Plate 1A). Through the Pliocene and early Pleistocene, the Oak Ridge fault had no topographic expression, but both sides of the fault subsided and received sediments, with the north side subsiding more (Yeats, 1965; 1988b). Yeats (1988a) calculated a slip rate of 5.9-12.5 mm/y since the end of Saugus deposition at 0.4-0.2 Ma.

The western half of Piru quadrangle contains part of segment 4. In this segment, the fault surface dips 64-77°S at depth but much shallower in the upper 2.5 km (Plate 2, A-A'). Strike and dip on the fault surface is highly irregular. Dibblee (1991) maps this segment along the mountain front, south of the trace of the fault on Plate 1B. However, subsurface mapping (Rieser, 1976) shows that the fault trace is north of the mountain front and has been eroded by the Santa Clara River. Within the Piru quadrangle, the fault zone is composed of fractured Modelo Formation (Huftile, 1988a, b). This segment juxtaposes Oligocene-Miocene Vaqueros Formation and older strata against Pliocene-Pleistocene Fernando and Saugus formations. The fault dips 70-75°S near Wiley Canyon (Plate 1A, Plate 2, B-B'), shallowing to

59°S near the surface, between Wiley and Eureka canyons with control as deep as 2.65 km (Plate 1A; Huftile, 1988a, b). This segment of the fault post-dates the folding of the Wiley Canyon anticline in the hanging-wall block because the fold axis is truncated by the fault (Huftile, 1988a, b).

The Wiley Canyon anticline is one of several en echelon folds in the hanging-wall block of the Oak Ridge fault. It plunges gently to the west and steeply to the east. With an east-trending cross section, Huftile (1988a, b) demonstrated that the Sespe Formation was broadly anticlinal when the Vaqueros Formation was deposited. This folding would have been coincident with tilting and normal faulting of the Sespe Formation at Big Mountain oil field (Hall et al., 1967; Canter, 1974). This pre-Vaqueros anticline was not necessarily parallel to the younger Wiley Canyon anticline.

To the east, in segment 5, the fault surface steepens to 83-85°, and the South and Middle strands diverge from the North strand (Plate 1A). West of Torrey Canyon, the South strand dips 78-90°S and juxtaposes Oligocene-Miocene Sespe and Vaqueros formations against middle and upper Miocene Modelo Formation. It has a separation of ~1220 m. The South strand trends southeast, extending south and southeast of the Piru quadrangle where it is rotated so that it dips north with normal separation, and is truncated by the Santa Susana fault (Ricketts and Whaley, 1975). The Middle strand trends southeast of the Oak Ridge fault. It dips 80°S near the North strand (Plate 2, D-D'), merges with the South strand, and is rotated to a north dip (Plate 2, E-E'; Ricketts and Whaley, 1975).

The North strand is generally a range-front fault that dips steeply to the south. The surface trace is commonly covered by landslide debris and alluvium (Plate 1A). The North strand is considered to be the younger strand because it cuts folded Fernando and Saugus formations (Yeats, 1988b). In the eastern part of Piru quadrangle, the North strand forms a north-facing scarp. A frontal strand is called the Camulos fault by Yeats (1988b); this strand may offset alluvium and cuts previously folded Fernando and Saugus formations.

Modelo lobe and East Ventura fold belt. The Modelo lobe extends between Sespe Creek (Figure 1) and Piru Creek (Plate 1A) and is almost entirely overlain by Modelo Formation at the surface. Miocene and older rocks are tightly folded providing closure for oil production within the Modelo Formation. Folds are 0.8-16 km in length and are roughly parallel to the San Cayetano fault (Çemen, 1977). An exception is the Buckhorn anticline which trends northwest at the western edge of the Piru quadrangle. It was mapped by Dibblee (1991) and Çemen (1977, 1989) to turn and trend west-southwest in the central part of the quad. But Morton (1972) showed much of that area to be covered with landslide debris, and subsurface cross sections A-A' and B-B' (Plate 2) show that the crest of the anticline is south of the location shown by Dibblee (1991) and Çemen (1977, 1989). There is a change in structural style between the two cross sections, with bedding-plane faulting in the west but only ramping in the east. This change in structural style can only be explained by the Buckhorn anticline trending obliquely to and dying out into the San Cayetano fault (Plate 1A).

Some of the folds extend across Piru Canyon, including the Holser syncline, Temescal anticline, and the Santa Felicia syncline, and thus they are transitional structures between the Modelo lobe and the East Ventura fold belt. Named folds within the Modelo lobe include the Pole Canyon anticline, Buckhorn syncline, Buckhorn anticline, Hopper Basin syncline, Modelo anticline, Blanchard syncline, and South Temescal anticline (Plate 1A). All of the larger, named anticlines have steeper or overturned south limbs, and the named synclines have steeper north limbs, implying southward vergence for the fold belt. South vergence is not always apparent for smaller, unnamed folds (Plate 2, A-A'). Most folds plunge to the east, exhibited by the general exposure of younger strata to the east (Plate 1A).

The Hopper Ranch fault (Plate 1A; Çemen, 1977, 1989) does not connect with the western San Cayetano fault north of Fillmore as mapped by Jennings and Strand (1969), rather it is likely a flexural-slip fault between the competent lower sandstone and incompetent lower shale members of the Modelo Formation (Çemen, 1977; Yeats, 1983). Its age is uncertain, but is assumed to be coincident with folding. Several folds, above and below the fault, are truncated by the fault.

The Arundell fault (Plate 1A; Çemen, 1977, 1989), like the Hopper Canyon fault, separates competent sandstones and incompetent shales of the Modelo Formation and is possibly a flexural-slip fault.

At the eastern termini of the Oak Ridge and San Cayetano faults, displacement is transferred to the East Ventura fold belt and the north-dipping Santa Susana fault (Figure 1). The eastern edge of the Piru quadrangle covers the westernmost part of the East Ventura fold belt. The fold belt is composed of east-trending, north-vergent folds and south-dipping reverse faults that may extend down into bedding-plane faults.

The Holser fault is the largest of the south-dipping reverse faults in the fold belt (Stitt and Yeats, 1983). In the Piru Canyon area, the Holser fault can be traced to Piru Canyon, but not across it (Figure 1, Plate 1A). West of Piru Creek, there is a south-side-up disturbed zone along the old road, just north of the Modelo Canyon fan. However, it makes little sense structurally because the Holser fault would be in the hanging-wall block of the Piru strand east of Piru Creek and in the hanging-wall block of the Main strand west of Piru Creek. In the Piru Creek area, the fault parallels bedding (Çemen, 1977; Weber, 1982; Stitt and Yeats, 1983; Yeats et al., 1985). Movement on the fault is entirely post-Saugus (Stitt and Yeats, 1983; Yeats et al., 1985). Reverse separation is 460-1850 m with the maximum separation at Ramona oil field in Val Verde quadrangle (Yeats et al., 1985).

The Del Valle fault is the only other south-dipping reverse fault in the East Ventura fold belt that extends westward into the Piru quadrangle. It is the southernmost reverse fault in the fold belt. Stratigraphic separation ranges from 400 m to 670 m (Yeats et al., 1985). Çemen (1977, 1989) mapped the Del Valle fault on the east side of Piru Canyon along the contact between Towsley and the Repetto member of the Fernando Formation. We have mapped the Towsley-Repetto contact north of Çemen's (1977, 1989) and the western Del Valle fault where he mapped the easternmost Main strand of the San Cayetano fault. This agrees with the mapping of Yeats et al. (1985) which shows, by offset contacts 1 km to the east of the Piru quadrangle, that that part of the fault must be south-side-up. The west end of the Del Valle fault is not associated with folding in either the hanging-wall or footwall blocks, implying that the fault is dying out to the west (Yeats et al., 1985).

Folds trend east-west, generally plunge to the east, and fold late Cenozoic strata. Northward vergence is evidenced by steeper north limbs of anticlines, steeper south limbs of synclines, and the convex northward surface traces of some folds such as the Santa Felicia syncline (Plate 1A; Yeats et al., 1985). The Holser syncline, exposed at the surface west of Piru Canyon, is overridden to the east of Piru Canyon by the Holser fault (Plate 2, F-F'; Yeats et al., 1985).

Santa Clara syncline. The Santa Clara River generally follows the axis of the Santa Clara syncline from southwest of Piru to the west. The eastern terminus of the Santa Clara syncline is southwest of Piru where an anticline-syncline pair, trending N70°W and named the Piru anticline and Piru syncline by Çemen (1977, 1989), occurs. These folds strongly deform the Pleistocene Saugus Formation (Plates 2, 3B). Comparison of Plate 3B with Plate XXI of Çemen (1977), shows that the axial planes of these folds dips south. Their trend is roughly perpendicular to maximum horizontal stress determined by borehole breakouts by Mount and Suppe (1987) in the East Ventura basin and may reflect the direction of transport. Çemen (1977) showed the trend of the Piru syncline changed trend to east-west at its northern end, but this change in trend was not supported by data; dipmeter data from the McCulloch Hopper Canyon 1A well infers that the syncline trends WNW throughout the Piru quadrangle. The folds plunge to the northwest, possibly from loading by movement on the San Cayetano fault.

CONCLUSIONS

Pre-Pliocene deformation in the Piru quadrangle is observed only in the hanging-wall block of the Oak Ridge fault. The north-dipping Torrey fault does not cut strata younger than Upper Mohnian (Ricketts and Whaley, 1975). The Sespe Formation in the Wiley Canyon anticline (Plate 1A) appears to have been broadly anticlinal at the time of Oligocene-Miocene Vaqueros Formation deposition (Huftile, 1988a, b). This fold was not necessarily parallel to the present Wiley Canyon anticline, and was refolded prior to movement on the Oak Ridge fault.

The Ventura basin is a Plio-Pleistocene accumulation of sedimentary rocks between opposing reverse faults, the San Cayetano and the Oak Ridge faults. Both faults cut strongly deformed Pleistocene Saugus Formation and appear to have Holocene offset. West-northwest-trending folds not parallel to the faults, the Piru anticline and the Piru syncline, occur in the footwall block, between the faults. So the depositional trough between the San Cayetano and Oak Ridge faults forms a zig-zag pattern synclinorium.

Fold axes of folds in the Modelo lobe, in the hanging-wall block of the San Cayetano fault, generally parallel the surface trace of the fault. The high frequency of folds may indicate a shallow décollement surface separating highly deformed Miocene strata from more competent strata; folded contacts in the northwest corner of the Piru quadrangle indicate that the décollement surface is in Miocene Modelo Formation Lower Shale member. These folds generally verge southward and plunge to the east; the eastward plunge is evidenced by generally younger strata to the east.

As the San Cayetano and Oak Ridge faults die out to the east, displacement is taken up by folds and south-dipping reverse faults of the East Ventura fold belt and by the north-dipping Santa Susana fault.

SEISMIC HAZARD

Post-Saugus faults include the San Cayetano, Oak Ridge, Holser and Del Valle faults. Relatively few tectonic landforms associated with the Holser and Del Valle faults have been preserved (Yeats et al., 1985). Thus, if these faults do produce earthquakes, their recurrence interval is very long; if these faults become bedding-plane faults at depth, they are unlikely to penetrate rocks of such high strength that they would generate large-magnitude earthquakes.

The faults with the greatest hazard in the area for seismic rupture are the San Cayetano and Oak Ridge faults. Both the Main and Piru strands of the San Cayetano fault appear to cut Holocene surfaces. The Main strand turns north at its east end and offsets the top of an alluvial fan at the mouth of Modelo Canyon. The Piru strand offsets alluvium to the west of, and in Piru. The two strands merge at depth and extend down at a moderate dip to seismogenic depth. There has been no historical seismicity on the onshore Oak Ridge fault. South of the Santa Clara Valley, the North strand of the Oak Ridge fault and the Camulos fault form a north-facing scarp and cut alluvium. East of Torrey Road (Plate 1A), alluvial deposits have a linear boundary with the Santa Clara River channel deposits. This could be related to faulting or merely be a terrace riser of the Santa Clara River. The landslides that cover much of the North strand are possibly coseismic. Seismicity on the San Cayetano fault has been recorded by Lee et al. (1979) and by Simila et al. (1987); G. W. Simila, written communication, 1989).

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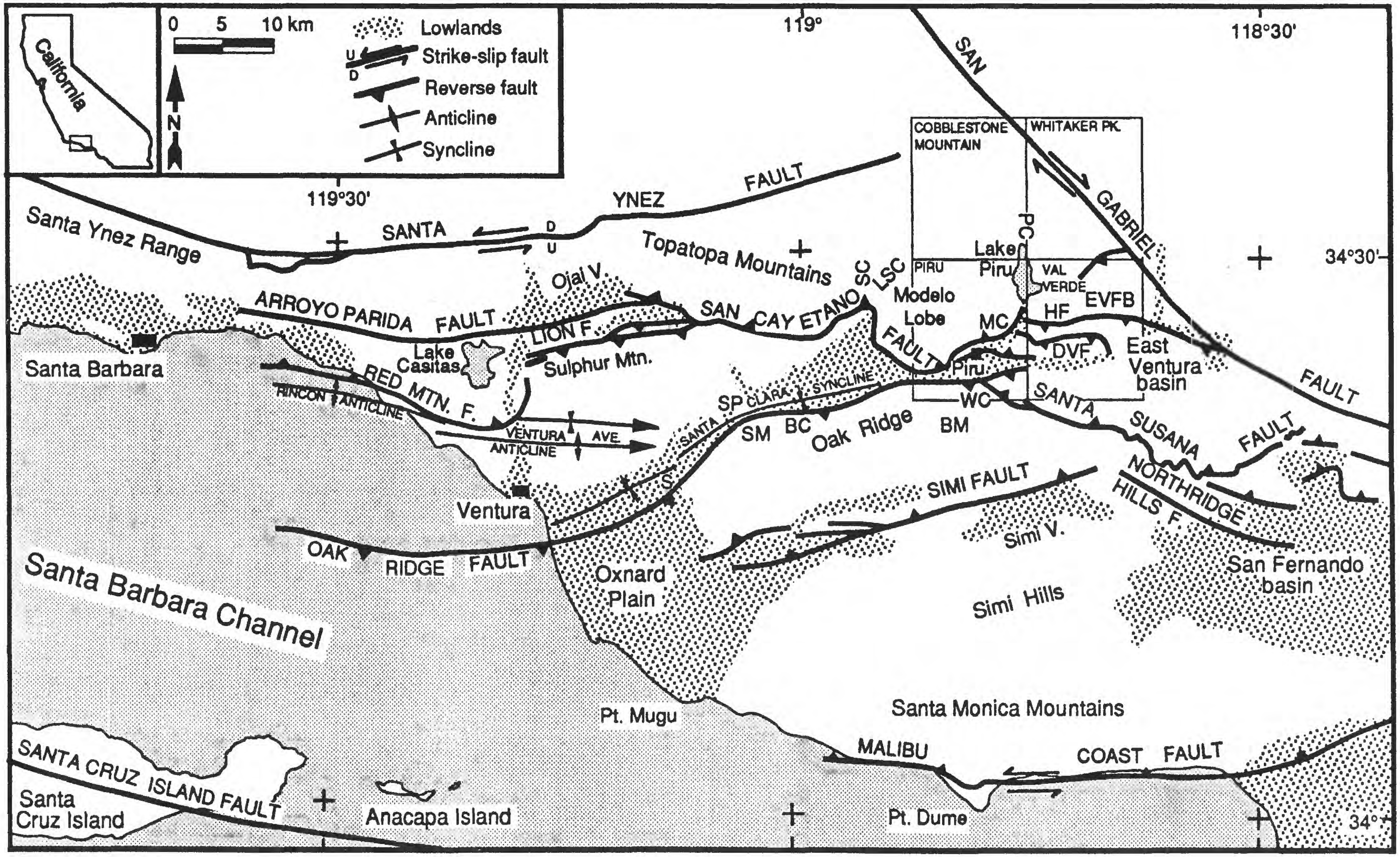
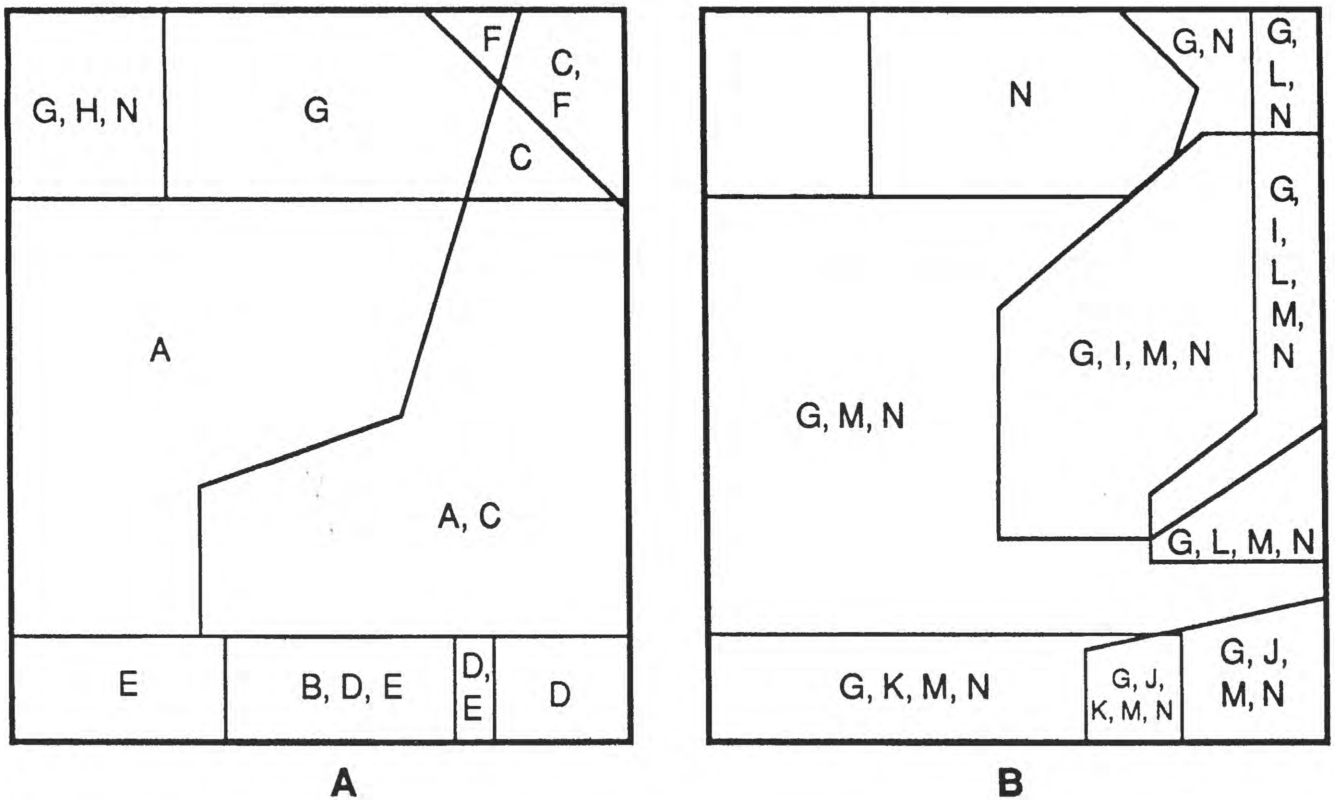
FIGURE CAPTIONS

Figure 1: Index map showing the major structural features of the Ventura basin and surrounding areas, and the location of the Piru quadrangle. BC-Balcom Canyon, BM-Big Mountain, DVF-Del Valle fault, EVFB-East Ventura fold belt, LSC-Little Sespe Creek, MC-Modelo Canyon, PC-Piru Creek, S-Saticoy, SC-Sespe Creek, SP-Santa Paula, WC-Wiley Canyon.

Figure 2: (A) Sources used extensively in compilation: A-Çemen (1977); B-Huftile (1988a, b); C-Huftile (1988, unpublished map); D-Ricketts and Whaley (1975); E-Rieser (1976); F-Crowell (1953, unpublished map); G-Argo Petroleum (1982); H-Bailey (1951, unpublished map); Morton (1972, entire quadrangle). (B) Sources consulted but not used extensively in compilation: I-Cordova (1956); J-Bain (1954); K-Jestes (1957); L-Robinson (1956); M-California Division of Mines and Geology (1972); Welsh (1972, unpublished map, entire quadrangle).


California
0 5 10 km
N
Lowlands
U
D
Strike-slip fault
Reverse fault
Anticline
Syncline
119°30'
119°
118°30'
34°30'
34°
SAN GABRIEL FAULT
COBBLESTONE MOUNTAIN
WHITAKER PK.
SANTA YNEZ FAULT
Santa Ynez Range
Topatopa Mountains
Ojai V.
ARROYO PARIDA FAULT
LION F.
SAN CAYETANO FAULT
SC
LSC
PIRU
Modelo Lobe
Lake Piru
PC
VAL VERDE
EVFB
HF
MC
DVF
East Ventura basin
Piru
WC
BM
SANTA SUSANA FAULT
Santa Barbara
Lake Casitas
Sulphur Mtn.
RED MTN. F.
RINCON ANTICLINE
VENTURA AVE. ANTICLINE
SANTA CLARA SYNCLINE
SP
SM
BC
S
Oak Ridge
SIMI FAULT
Simi V.
NORTHRIDGE HILLS F.
San Fernando basin
Ventura
OAK RIDGE FAULT
Oxnard Plain
Simi Hills
Santa Barbara Channel
Pt. Mugu
Santa Monica Mountains
MALIBU COAST FAULT
SANTA CRUZ ISLAND FAULT
Santa Cruz Island
Anacapa Island
Pt. Dume
Figure 1


G, H, N
G
F
C,
F
C
A
A, C
E
B, D, E
D,
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D
A
G, N
G,
L,
N
N
G,
I,
L,
M,
N
G, I, M, N
G, M, N
G, L, M, N
G, K, M, N
G, J,
K, M, N
G, J,
M, N
B

Figure 2