The northern Los Angeles basin is influenced by two structural styles: the west-trending compressional Transverse Ranges to the north, and the strike-slip Peninsular Ranges to the south. The interaction of these two structural styles has resulted in a complex fold/fault belt at the northern margin of the Los Angeles basin, which deforms a variable sequence of late Miocene through Quaternary marine strata.

Subsurface mapping of Quaternary marine gravels by electric-log correlation documents the latest phase of deformation in the northern Los Angeles basin. The Quaternary marine gravels are folded at the Wilshire arch, the Hollywood basin, the central trough, the Newport-Inglewood fault, and the Santa Monica fault. The west-plunging Wilshire arch, which follows Wilshire Boulevard east of the Newport-Inglewood fault, is a broad fold identified and named in this study. Deformation of the Wilshire arch, which is underlain and caused by the potentially-seismogenic Wilshire fault, began around 0.8 - 1.0 Ma. A fault-bend fold model, based on the shape of the Wilshire arch, indicates a dip-slip rate of 1.5 - 1.9 mm/yr for the Wilshire fault, whereas a three-dimensional elastic dislocation model indicates a right-reverse slip rate of 2.6 - 3.2 mm/year for the Wilshire fault.

The finer-grained marine Pliocene strata include the late Pliocene to early Pleistocene Pico member, and the early Pliocene Repetto member, of the Fernando Formation. Thickness and lithology variations in the Pico and Repetto strata, which were influenced by syndepositional structures, indicate that the entire Pliocene and the latest
Miocene were characterized by compression. The primary structure present throughout the Pliocene is a south-dipping monocline, which was underlain and caused by a deep reverse fault, dipping ~55 - 60° to the north, referred to here as the Monocline fault. Relative subsidence of the central trough resulted in deposition of up to 7000 ft (2135 m) of Pico strata, and up to 5000 ft (1525 m) of Repetto strata, compared to zero deposition on the monoclinal high. In the western part of the study area, the south-dipping monocline is interrupted by the secondary East Beverly Hills fold, which may be a rabbit-eared fold that accommodates excess volume by bedding-parallel slip. The East Beverly Hills fold was active in the latest Miocene through Pliocene, and was most active during early Pliocene Repetto deposition. In the eastern part of the study area, the monocline is interrupted by the Las Cienegas fold, which formed in the hangingwall of the Las Cienegas fault. The Las Cienegas fault was a normal fault in the late Miocene, and was reactivated in the Pliocene as a steep reverse fault. Folding and uplift on the Las Cienegas anticline occurred throughout the Pliocene, with the greatest amount occurring during lower and lower-middle Pico deposition.
Subsurface Quaternary and Pliocene Structures of the Northern Los Angeles Basin, California

By

Cheryl Hummon

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CHAPTER 1: INTRODUCTION

The purpose of this study is to increase our understanding of the active, seismogenic faults that underlie the northern Los Angeles basin. The primary means of accomplishing this is by subsurface mapping of stratigraphy and structures using oil-well data. Subsurface mapping allows us to identify active and older faults, using direct and indirect methods, and to estimate slip rates for the faults. With structure contour maps, isopach maps and cross section, we unravel the complex structural evolution of the northern Los Angeles basin.

Several people are working together on this project, because of the complexity of the structures and stratigraphy, and because of the overwhelming amount of data. From west to east on Figure 1.1 (A, B, C), the contributions of the various workers are as follows. (A) Between the Riviera oil field and the Newport-Inglewood fault, Hiroyuki Tsutsumi (PhD work, starting 1992, Oregon State University) is working on the pre-Quaternary stratigraphy and structure, and Cheryl Hummon (this thesis, Chapter 2) has worked on the Quaternary. (B) From the Newport-Inglewood fault to the western Las Cienegas field, Craig Schneider (MS, 1994, Oregon State University) has worked on the pre-Pliocene structure and stratigraphy and on the structural evolution of the Neogene and Quaternary. Hummon (this thesis, Chapters 2, 3, and 4) has worked on the Quaternary and Pliocene stratigraphy and structures, and also on the structural evolution of the late Neogene and Quaternary. (C) The eastern Las Cienegas field and the LA City - LA Downtown fields will be mapped starting in 1994. The Quaternary section was already mapped (Hummon, this thesis, Chapter 2) for the western part of this area.
Figure 1.1. Study area in the northern Los Angeles basin, showing oil fields and regions analyzed by the various workers involved in this project. Area A (Tsutsumi and Hummon) includes Riviera (R), Sawtelle (Sa), Cheviot Hills (CH), West Beverly Hills (WBH), Culver City (CC), and northern Inglewood (In) oil fields. Area B (Hummon and Schneider) includes East Beverly Hills (EBH), San Vicente (SV), Sherman (Sh), Salt Lake (SL), South Salt Lake (SSL), and western Las Cienegas (LC) oil fields. Area C (Tsutsumi and Hummon) includes Las Cienegas (LC), LA Downtown (LAD) and LA City (LAC) oil fields. Location of this map is shown on Figure 1.2 (study area). N-I fault = Newport-Inglewood fault.
Figure 1.2. Major geologic features of the Los Angeles basin. Dotted box locates area of this study. Faults are: HF = Hollywood fault; NIF = Newport-Inglewood fault; PVF = Palos Verdes fault; RHF = Raymond Hill fault; SMF = Santa Monica fault; WF = Whittier fault. PVH = Palos Verdes Hills; SMM = Santa Monica Mountains. Locations of stratigraphic sections used for age-control (Blake, 1991) are: M = Malaga Cove; N = Newport Bay (actually located under the focal mechanism); R = Repetto Hills; T = Topanga Canyon. Arrows show relative displacement on strike-slip faults. Earthquake focal mechanisms (from Hauksson, 1990) are: L, 1933 Long Beach (ML = 6.3); W, 1987 Whittier Narrows (ML = 5.9). Bold arrow indicates relative Pacific - North American plate motion (~5 cm/yr), from DeMets et al. (1990).
Because of the close association between Hummon's Plio-Quaternary research and Schneider's pre-Pliocene research in area B, both theses will include a complete set of plates by both authors. All six cross sections (A-A' through F-F'; Plates 2 through 7) were constructed by Hummon and Schneider. Additional cross sections, presented as figures, are labeled in order of presentation, starting with G-G'. Two structure contour maps were completed by Hummon (Fig. 2.1; Plate 8), and four by Schneider (Plates 9 through 12). Two isopach maps were constructed by Hummon (Plates 13 and 14), and two by Schneider (Plates 15 and 16).

Chapter 1 of this thesis is an introduction to the geologic setting and history of the Los Angeles basin, written by Hummon. Chapter 2 presents the Quaternary research. Most of Chapter 2 is a combination of Hummon et al. (1992; in Association of Engineering Geologists annual meeting proceedings volume) and Hummon et al. (1994; in the April, 1994 issue of Geology). The 1992 AEG paper includes work by Hummon (80%), Schneider (10%), and Yeats/Huf tile (10%). The 1994 Geology paper includes work by Hummon (40%), Schneider (40%), Yeats/Huf tile (10%), and Dolan/Sieh (10%). Chapter 3 (by Hummon) explains the data sources and methods used in the Pliocene research. Chapter 4 (by Hummon) presents the results of the Pliocene research.

The data used in this study are primarily from the oil industry, which generally presents measurements in feet. Therefore, thicknesses and depths in this study are presented in feet, with metric equivalents in parentheses. Chapter 2 is an exception, with all measurements presented in metric, because the journal Geology uses metric values.
PRESENT-DAY TECTONIC SETTING OF THE LOS ANGELES BASIN

The central trough of the Los Angeles basin is filled with more than 32,000 ft (10 km) of Neogene and Quaternary sediments (Yerkes et al. 1965) that reflect its complex tectonic and structural evolution. The Los Angeles basin lies in a tectonically active area affected by the interaction of two distinct structural styles (Fig. 1.2). South of the Los Angeles basin are the Peninsular Ranges, with right-lateral strike-slip faults parallel to the Pacific - North American relative plate motion. The Los Angeles basin is dominated by active NW-trending right-lateral strike-slip faults, such as the Whittier fault and the Newport-Inglewood fault; on which the 1933 Long Beach earthquake occurred (Fig. 1.2; Hauksson, 1990).

North of the Los Angeles basin, active west-trending reverse faults of the Transverse Ranges result from local convergence associated with the big bend in the San Andreas fault. The southernmost Transverse Ranges form the northern margin of the Los Angeles basin, marked by the active Santa Monica - Hollywood - Raymond Hill fault system (Fig. 1.2). West-trending reverse faults of the Transverse Ranges extend into the northern Los Angeles basin as blind thrusts (Wright, 1991), including the Elysian Park thrust (Davis et al., 1989; Lin and Stein, 1989), on which the 1987 Whittier Narrows earthquake occurred (Fig. 1.2; Hauksson, 1990).

The interaction of the strike-slip and reverse-slip structural styles results in an active fold-thrust belt in the northern Los Angeles basin, involving Miocene, Pliocene, and Quaternary strata. Farther south in the Los Angeles basin, the right-lateral strike-slip faulting of the Peninsular Ranges dominates (Wright, 1991). This change is reflected in the orientation of the maximum, intermediate, and minimum principal stresses ($\sigma_1$, $\sigma_2$, and $\sigma_3$, respectively). In the northern Los Angeles basin, $\sigma_1$ is horizontal and trending ~N13E, $\sigma_2$ is horizontal, and $\sigma_3$ is vertical, with $\sigma_1 > \sigma_2 \approx \sigma_3$ (Hauksson, 1987, 1990). This orientation allows strike-slip and reverse faulting, which are found in Quaternary structures as well as historical seismicity in the northern Los Angeles basin (Hauksson, 1987, 1990). In the southern Los Angeles basin, $\sigma_1$ is horizontal, trending ~N23E (Hauksson, 1987), $\sigma_2$ is vertical, with $\sigma_1 > \sigma_2 > \sigma_3$. This orientation is consistent with the strike-slip and normal-fault Quaternary structures and seismicity of the southern Los Angeles basin (Hauksson, 1987, 1990). Fold axes that formed during the Plio-Pleistocene compressional phase in the Los Angeles basin are approximately perpendicular to today's $\sigma_1$ (Hauksson, 1990), suggesting that the
present-day stress field was present throughout the Plio-Pleistocene compressional phase. Davis et al. (1989) suggested that compression began between 2.2 and 4.0 Ma, but this study indicates that the compressional phase began around 5 Ma (see Chapter 4). Mount and Suppe (1992) found that the orientation of Quaternary fold axes in other parts of southern California are also consistent with the present-day state of stress.

The coexistence of compressional and strike-slip structures in the Los Angeles basin has been attributed to wrench-style faulting (Wilcox et al., 1973), where compressional structures were considered secondary to, and caused by, underlying strike-slip faults. More recently, strain partitioning, with two coexisting sets of structures accommodating the strike-slip and reverse components of strain, has been proposed for the Los Angeles basin (Hauksson, 1987, 1990; Mount and Suppe, 1987, 1992; Wright, 1987; Namson and Davis, 1988; Crouch and Suppe, 1993). Hauksson (1990) noted that moderate and large earthquakes in the Los Angeles basin rarely exhibit oblique faulting.

Convergence rates across the Los Angeles basin are estimated by two methods that yield overlapping ranges. GPS/VLBI measurements indicate 5.0 ± 1.2 mm/yr (Feigl et al., 1993) to 7 mm/yr (Ken Hudnut, pers. comm., 1993) of shortening across the Los Angeles basin. Based on retrodeformable cross sections, Davis et al. (1989) estimated the convergence rate between Palos Verdes Hills and the San Andreas fault (a distance ~1.5 times the distance across the Los Angeles basin) at 5.4 - 13.5 mm/yr, averaged over the last 2.2 - 4.0 Ma.
MAJOR ACTIVE STRUCTURES OF THE NORTHERN LOS ANGELES BASIN

Newport-Inglewood fault

The right-lateral Newport-Inglewood fault is accompanied by a 10- to 15-km-wide diffuse zone of seismicity that corresponds roughly to the near-surface location of the fault (Hauksson, 1987, 1990). Compared to other faults in the Los Angeles basin and their slip rates, the rate of seismicity of the Newport-Inglewood fault is high (Hauksson, 1990). Ziony and Yerkes (1985) estimated the late Quaternary slip rate on the Newport-Inglewood fault at ~1 mm/yr. The seismicity (Real, 1987; Hauksson, 1987, 1990) and orientation (parallel to relative Pacific - North American plate motion) of the Newport-Inglewood fault suggest that it is predominantly a right-lateral strike-slip fault. Striae in well cores in the Inglewood oil field (Driver, 1943) indicate that the most recent movement on the Newport-Inglewood fault was predominantly strike-slip. Weldon and Humphreys (1986) suggest that the NW-trending right-lateral strike-slip faults of the Los Angeles basin (the Newport-Inglewood, Whittier, and Palos Verdes faults; Fig. 1.2) may accommodate 10-15% of the Pacific - North American relative plate motion.

The history of the Newport-Inglewood fault remains somewhat speculative. Yerkes et al. (1965) cited evidence of late middle Miocene offset in the Long Beach and West Newport oil fields. The Newport-Inglewood fault may have been active since the middle Miocene (Conrey, 1967; Barrows, 1974; Campbell and Yerkes, 1976), but Conrey (1967) found that latest Miocene and earliest Pliocene submarine fans were not affected by the Newport-Inglewood fault. Right-lateral strike-slip faulting with associated anticlinal flexures apparently began forming in the middle Pliocene (Slosson, 1958; Crowell, 1987; Wright, 1991), based on changes in thickness and lithology. In the Inglewood field, 3000 - 4000 ft (900 - 1200 m) of post-middle Pliocene right-lateral strike-slip offset has been reported by Poland et al. (1959), Yerkes et al. (1965), Wright (1973, 1991), and Castle and Yerkes (1976). Castle and Yerkes (1976) reported 1500 - 2000 ft (460 - 610 m) of Quaternary right-lateral slip. Recent oblique slip is suggested by the presence of ~1000 ft (~300 m) of vertical separation of Pliocene strata (Poland et al., 1959; Yerkes et al., 1965). Castle and Yerkes (1976) noted ~200 ft (61
m) of vertical separation and 100 - 150 ft (30 - 45 m) of right-lateral displacement in the latest Quaternary.

Santa Monica - Hollywood fault

The active Santa Monica - Hollywood fault system (Fig. 1.2) is generally believed to have primarily reverse slip, with zero to <50% left slip (Ziony and Yerkes, 1985; Real, 1987; Davis et al., 1989; Wright, 1991). The Santa Monica and Hollywood faults are remarkably aseismic, with deformation and seismicity in the northern Los Angeles basin concentrated in the basin-margin fold belt just to the south (Chapter 2; Hauksson and Saldivar, 1989; Hauksson, 1990). Trenching and tectonic geomorphology suggest that the Santa Monica fault is a left-reverse transpressional fault (Dolan et al., 1992) and that the Hollywood fault may also have a large left-lateral component (Dolan et al., 1993).

The Santa Monica - Hollywood fault system has undergone a significant amount of left slip during the Neogene, but there is considerable variation in the estimates of slip and timing. Yeats (1968a, 1976) estimated that a lower Miocene shoreline was offset 55 mi (90 km) by left slip on the Santa Monica - Hollywood fault system, before the early middle Miocene. Barbat (1958) recognized ~8 mi (~13 km), and Lamar (1961) estimated ≤11 mi (≤17.6 km), of pre- late Miocene left slip on the Santa Monica - Hollywood fault. Lamar (1961) estimated ≥7 mi (≥11 km) of late Miocene to early Pliocene left slip, based on a comparison of thicknesses, facies, current directions of late Miocene strata. Lamar (1961) and Campbell and Yerkes (1976) concluded that reverse slip increased, and left slip was negligible, during the Plio-Pleistocene. Truex (1976) reported 33 mi (53 km) of middle Miocene left slip, and 4 mi (6 km) of post-late Miocene left slip. The late Miocene Tarzana fan, whose source channel was in the position of today's Santa Monica Mountains, has been displaced 6-9 mi (10-15 km) (Sullwold, 1960) or 10 mi (16 km) (Redin, 1991) in a left-lateral sense along the Santa Monica - Hollywood fault. Estimates of total left slip along the Santa Monica - Hollywood fault range from 18 mi (30 km) (Crouch and Suppe, 1993), to 35 mi (60 km) (Luyendyk and Hornafius, 1987), to 55 mi (90 km) (Yeats, 1968a, 1976; Campbell and Yerkes, 1976; Crowell, 1987).
Northern Los Angeles basin fold-fault belt

The subsurface structure of the northern Los Angeles basin fold-fault belt is the subject of this study. Chapters 2, 3, and 4 (this study) and Schneider (1994) present the results of subsurface mapping of Neogene and Quaternary strata and structures in the northern Los Angeles basin.
TECTONIC, STRUCTURAL, AND STRATIGRAPHIC HISTORY OF THE LOS ANGELES BASIN

The purpose of this study is to interpret the Pliocene and Quaternary structural and stratigraphic evolution of the northern Los Angeles basin. Because active structures have influenced the lithology and distribution of strata in the Neogene and Quaternary (Yerkes et al., 1965; Conrey, 1967; Lamar, 1970; Wright, 1991), this section introduces major structural and depositional patterns together. While the emphasis of this chapter is the Pliocene and Quaternary, it is necessary to put this recent geologic history into perspective with an overview of the preceding tectonic and structural evolution. A brief review of the pre-Pliocene geology is followed by a more complete discussion of Plio-Pleistocene tectonics, structure, and stratigraphy. Pre-Pliocene tectonics, structure and stratigraphy are covered in greater detail by Lamar (1961), Yerkes et al. (1965), Wright (1991), and Schneider (1994). Figure 1.3 summarizes various aspects of the Neogene and Quaternary strata in the Los Angeles basin, including thickness, environment of deposition, lithology, and subsidence (after Yerkes et al., 1965; Blake, 1991).

An important aspect of the following discussion is that much of the "dating" and correlation of strata is by benthic foram stages. Decades of research and literature have presented the stratigraphic and structural history of the Los Angeles basin in terms of benthic foram stages. Benthic foram stages are environmental indicators that do not strictly represent time lines, but broadly reflect the changing conditions in the Los Angeles basin over time. In some localities in the Los Angeles basin, a benthic-foram "age" has been established or corroborated by a chronostratigraphic dating or correlation method. A discussion of Pliocene dating methods follows this review of tectonics, structure and stratigraphy.

Pre-Miocene

During the Mesozoic and Paleogene, southwestern California was a convergent plate boundary, with the (now-subducted) Farallon Plate subducting eastward beneath the North American Plate (Atwater, 1970). Mesozoic crystalline basement rocks include metamorphic rocks (Catalina Schist; Santa Monica Slate) and intrusions,
**Figure 1.3.** Summary of Neogene and Quaternary stratigraphy of the Los Angeles basin. Lithologic abbreviations: sst = sandstone; sltst = siltstone; sh = shale. U = upper; M = middle; L = lower. After Yerkes et al. (1965) and Blake (1991).
summarized by Sorensen (1984, 1985) and Wright (1991). Late Cretaceous and Paleogene strata in the Los Angeles area were deposited in basins related to the active subduction zone. Only one occurrence of probable late Cretaceous through early Miocene strata is known in this study area: the Morgan Brown U-6-1 well (cross section A-A', Plate 2) has ~600 ft (~180 m) of redbeds, interpreted to be late Eocene to early Miocene Sespe formation (Morgan Brown, Inc. interpretation, 1959; Lamar, 1961) or Paleocene in age (Yeats, 1973).

**Early and middle Miocene**

Between 29 and 20 Ma, the East Pacific Rise reached the subduction zone of western North America, initiating a strike-slip plate boundary between the Pacific and North American plates (Atwater, 1970; Crowell, 1987; Sedlock and Hamilton, 1991). As a result, the dominant tectonic feature of the early and middle Miocene Los Angeles basin area was the underlying, recently-subducted East Pacific Rise (Yeats, 1968b, Atwater, 1970; Blake et al., 1978; Wright, 1991). In the early and middle Miocene, the Los Angeles basin area underwent crustal extension and rifting in a transtensional plate setting (Yeats, 1968b; Atwater, 1970; Turcotte and McAdoo, 1979; Crowell, 1987; Mayer, 1987; Yeats, 1987; Sedlock and Hamilton, 1991; Wright, 1991; Crouch and Suppe, 1993), accompanied by subsidence (Yerkes et al., 1965; Blake et al., 1978; Campbell and Yerkes, 1976; Crowell, 1987; Mayer, 1987; Yeats, 1987; Sedlock and Hamilton, 1991; Wright, 1991). Middle Miocene crustal extension and rifting have been inferred from widespread volcanic rocks (Yerkes et al., 1965; Campbell and Yerkes, 1976; Crowell, 1987; Yeats, 1987; Sedlock and Hamilton, 1991; Wright, 1991; Crouch & Suppe, 1993). The middle Miocene Topanga Group, with interbedded volcanics, volcanioclastic sediments, unconformities, and rapid facies changes (Lamar, 1961; Yerkes et al., 1965), reflects the unstable tectonic environment of an actively riftinng basin (Wright, 1991). Crustal extension and subsidence were accommodated by normal faulting during the middle Miocene and early late Miocene in the Los Angeles basin (Yerkes et al., 1965; Campbell and Yerkes, 1976; Blake et al., 1978; Crowell, 1987; Yeats, 1987; Davis et al., 1989; Wright, 1991; Crouch & Suppe, 1993).
Late Miocene

In the late Miocene, the Los Angeles basin area was no longer influenced by the East Pacific Rise, but significant subsidence continued in a transtensional plate setting. An increase in the extensional component of relative plate motion, around 10.5 Ma (Stock and Molnar, 1988), may have contributed to ongoing extension and subsidence (Blake et al. 1978; Mayer, 1987; Sedlock and Hamilton, 1991; Wright, 1991; Yeats and Beall, 1991). Subsidence rates exceeded deposition rates (Ingle, 1980; Mayer, 1987), resulting in a gradual deepening of the basin from 1600 ft (500 m) (Natland and Rothwell, 1954) in the early late Miocene, to 3000 - 4000 ft (1000 - 1220 m) in the latest Miocene (Natland, 1952; Natland and Rothwell, 1954; Yerkes et al., 1965), based on benthic forams. A lower Mohnian (late middle Miocene and early late Miocene) nodular-shale lithology (Yerkes et al., 1965; Wright, 1991) resulted from slow deposition in a reducing environment. Upper Mohnian (upper Miocene) strata, however, show an increase in sediment supply, with the deposition of turbidite sandstone as part of the Tarzana submarine fan in the northwestern Los Angeles basin (Sullwold, 1960; Lamar, 1961, 1970; Redin, 1991). Benthic forams indicate that the water depth during deposition of the Tarzana fan was about 3000 ft (1000 m) (Natland and Rothwell, 1954; Sullwold, 1960).

Latest Miocene

The beginning of the Los Angeles basin, as we know it today, is generally considered to be the time that sediments were deposited in the same pattern as today, with subsidence in a deep central trough. The timing of transition in depositional pattern has been estimated at latest Miocene to early Pliocene (~7 Ma) (Lamar, 1961; Yerkes et al., 1965; Ingle, 1980; Blake, 1991; Wright, 1991), during deposition of upper Mohnian (Yeats and Beall, 1991) or Delmontian (Yeats, 1978; Ingle, 1980) strata. An isopach map of late Miocene strata (Yeats and Beall, 1991) shows that the area of accelerated subsidence was oriented nearly north-south, with a sediment source in the northeast Los Angeles basin (Lamar, 1961; Yeats and Beall, 1991). Deposition was not confined to the area of the Pliocene and present-day Los Angeles basin. The late Miocene increase in subsidence may have been caused by thermal subsidence upon cooling of crust that was thinned and extended in the middle Miocene (Turcotte and...
McAdoo, 1979; Crowell, 1987; Mayer, 1987). Thermal subsidence alone is not an adequate explanation, however, because it would cause rapid then slowing subsidence, not the increasing subsidence suggested for the Los Angeles basin (Yeats, 1978). A large component of fault-related subsidence and uplift must have been present during the late Miocene and early Pliocene (7 - 4 Ma), when significant uplift on the Santa Monica Mountains and basin-margin folding and reverse faulting began (Yerkes et al., 1965; Wright, 1991).

Early Pliocene

Isopach maps show that the Los Angeles central trough achieved its present northwest orientation, and the location of basin margins became similar to today's, near the beginning of the Repettian (Yeats and Beall, 1991), or about 4 - 5 Ma (Blake, 1991; Yeats and Beall, 1991). This change, which was marked by an acceleration of basin subsidence (Yerkes et al., 1965; Yeats 1978; Ingle, 1980; Crowell, 1987; Wright, 1991; Yeats and Beall, 1991), was linked to a shift in plate motions that accompanied the opening of the Gulf of California at around 4 - 5 Ma (Atwater, 1970; Campbell and Yerkes, 1976; Yeats 1978; Ingle, 1980; Crowell, 1987; Sedlock and Hamilton, 1991; Yeats and Beall, 1991; Wright, 1991). This shift in relative plate motion added a compressional component to the largely strike-slip plate boundary (Atwater, 1970; Engebretson et al., 1985; Harbert, 1991), and marked the beginning of the big bend in the San Andreas fault (Atwater, 1970; Yeats, 1978; Sedlock and Hamilton, 1991) and accompanying uplift and shortening of the Transverse Ranges (Atwater, 1970; Yeats, 1978; Crowell, 1987; Davis et al., 1989).

Water depths in the Los Angeles basin reached a maximum in the early Pliocene Repettian stage (Slosson, 1958; Yerkes et al., 1965; Crowell, 1987; Mayer, 1987; Yeats and Beall, 1991; Blake, 1991), when subsidence rates were greater than deposition rates, allowing a deep basin to form. Repettian benthic forams indicate that water depths reached lower bathyal to abyssal depths (Natland, 1952; Blake, 1991) of >4000 ft (>1220 m) (Natland, 1952; Natland and Rothwell, 1954), or around 6000 ft (1830 m) (Natland and Rothwell, 1954; Slosson, 1958; Yerkes et al., 1965), with the deepest part ≤8000 ft (2440 m) (Slosson, 1958; Conrey, 1967; Ingle, 1980). The basin shallowed to 4000 ft (>1220 m) at the end of the Repettian (Natland and Rothwell, 1954; Slosson, 1958; Conrey, 1967).
In the early Pliocene (Repettian) Los Angeles basin, sediment transport and deposition were primarily by turbidity currents, with coarse-grained proximal facies and fine-grained distal facies (Slosson, 1958; Yerkes et al., 1965; Conrey, 1967). More than 5000 ft (1500 m), or possibly more than 8000 ft (2440 m) (Yeats and Beall, 1991) of sand, silt, and local conglomerate were deposited in the central trough (Slosson, 1958; Yerkes et al., 1965; Conrey, 1967). The thickest and coarsest deposits were deposited in the central trough and at the turbidite fan entry point at Montebello, in the northeastern Los Angeles basin (Slosson, 1958; Lamar, 1961; Yerkes et al., 1965; Conrey, 1967). Secondary fans were located along the northern and eastern margins of the basin (Slosson, 1958; Yerkes et al., 1965; Conrey, 1967). The sediment sources for the Los Angeles basin were the San Gabriel Mountains and the Peninsular Ranges (Slosson, 1958; Conrey, 1967).

The margins of the early Pliocene Los Angeles basin were in a similar location as those of today's physiographic basin (Slosson, 1958; Yerkes, et al., 1965; Conrey, 1967). Thinned strata, angular unconformities, and localized slumping occurred at the basin margins, where the depositional gradients were 6 - 10°, and locally up to 15 - 20° (Slosson, 1958; Conrey, 1967). The Santa Monica Mountains were above sea level during the early Pliocene, based on the presence of localized conglomerates containing clasts derived from the Santa Monica Mountains (Conrey, 1967). Conrey (1967) also reported a local increase in grain size, high quartz/feldspar ratios, and increased angularity of granules in the northern Los Angeles basin, indicating uplift of the Santa Monica Mountains.

Late Pliocene and early Pleistocene

The structural and depositional patterns established in the early Pliocene continued through the rest of the Pliocene and Quaternary (Yerkes et al., 1965; Crowell, 1987; Blake, 1991; Yeats and Beall, 1991), when deposition exceeded subsidence (Natland and Rothwell, 1954; Slosson, 1958; Yerkes et al., 1965; Blake, 1991), filling the Los Angeles trough with sediments from the uplifting Transverse Ranges (Ingle, 1980; Mayer, 1987). Mayer (1987) suggested that continued subsidence was caused by sediment loading only, not by tectonic forces. Yeats (1978), however, found that tectonic subsidence rates in the Los Angeles basin have increased through the Pliocene and Quaternary.
Late Pliocene strata represent a middle bathyal to inner neritic basin-filling sequence (Blake, 1991). Venturian benthic forams indicate that water depths shallowed from 3000-4000 ft (915-1220 m) during the late Pliocene (Natland, 1952; Natland and Rothwell, 1954; Slosson, 1958; Yerkes et al., 1965) to 2000 ft (610 m) (Natland, 1952). Wheelerian benthic forams (middle and upper Pico of Wissler, 1943), which are approximately early Pleistocene in age (Blake, 1991), indicate that water depths shallowed from 2000 ft (610 m) (Natland, 1952) to 900 ft (275 m) (Natland, 1952; Natland and Rothwell, 1954; Yerkes et al., 1965).

In the central trough, an estimated 7900 ft (2400 m) of upper Pliocene to lower Pleistocene (Pico) strata were deposited (Yerkes et al., 1965). Deposition of sand, silt, and minor conglomerate continued, and sediment sources were more localized than during the early Pliocene (Yerkes et al., 1965). Local unconformities formed as a result of uplift and compression at the basin margins (Slosson, 1958; Yerkes et al., 1965).

**Late Pleistocene and Holocene**

During the late Pleistocene and Holocene epochs, the subsidence and depositional trends of the late Pliocene and early Pleistocene continued, with subsidence of the central trough and compression of the basin margins (Yerkes et al., 1965). Yeats (1978) found that the maximum tectonic subsidence rate occurred in the last 1.0 m.y. in the Los Angeles basin. The late Pleistocene shoreline receded, with water depths decreasing from inner neritic to nonmarine (Blake, 1991), or from 900 ft (275 m) to 0 ft (0 m) in the Hallian benthic foram stage (Natland, 1952). The marine basin became filled with sediment (Ingle, 1980; Blake, 1991) until lagoonal, nonmarine, terrace, and alluvial sediments were deposited (Yerkes et al., 1965). Additional information about Quaternary strata in the Los Angeles basin is presented in Chapter 2.
Establishment and use of benthic foram stages

Neogene and Quaternary stratigraphy in the Los Angeles basin is primarily defined by benthic foraminalferal stages. The Miocene benthic foram stages (summarized on Figs. 1.3 and 1.4) were established by Kleinpell (1938, 1980; Luisian, Mohnian and Delmontian stages are present in this study area) and Wissler (1943, 1958; Divisions A through F). The Pliocene benthic foram stages (summary, Fig. 1.3; details, Fig. 1.4) were established by Wissler (1943, 1958; Repetto and Pico divisions) and Natland (1952; Repettian, Venturian, Wheelerian, Hallian Stages). In the Los Angeles basin, the oil industry follows Wissler's (1943) use of Repetto and Pico for the Pliocene and lower Pleistocene strata.

Benthic forams are environmental indicators that reflect water depth, and secondarily, energy, oxygen and temperature. The Miocene and Pliocene benthic foram stages of the Los Angeles and Ventura basins have modern analogs in the offshore basins of southern California (Crouch, 1952; Natland, 1952; Conrey, 1967; Ingle, 1980; Wright, 1991). Because benthic forams are environmental indicators, the stages they define may be time-transgressive (Natland, 1952; Lamar, 1961, 1970; Bandy, 1971; Blake, 1991; Wright, 1991), especially near basin margins (Natland, 1952; Ponti et al., 1993) or over large areas. The region covered in this study is small (<100 km²), but includes the Pliocene basin margin, which may complicate interpretations of benthic foram stages (see Chapter 4).

Benthic forams have been used extensively in the Los Angeles basin to define stratigraphy, despite the serious drawback of possible time-transgression. For the Miocene strata, most of the benthic foram correlations correspond to lithologic changes. The Pliocene Repetto and Pico strata, however, cannot be distinguished on the basis of lithology (Natland, 1952; Lamar, 1961) except locally, and are therefore grouped together as the Fernando Formation. In this study, the Pliocene and lower Pleistocene strata are referred to as the Repetto (lower Fernando) and Pico (upper Fernando) members of the Fernando Formation. The terms Repetto and Pico are used in this study, because the oil industry (our data) uses these terms, and because "upper Repetto" is simpler than "upper upper Fernando".
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1 from Wissler (1943)
2 from Wissler (1958)
3 from Natland (1952)

Figure 1.4. Benthic foram stages of the northern Los Angeles basin, emphasizing Pliocene Repetto and Pico strata. Faunal marker indicates first downward occurrence of the foram. Summarized from Wissler (1943, 1958) and Natland (1952).
Constraints on ages of benthic foram stages

In some localities of the Los Angeles basin, the age of the Pliocene benthic foram stages is constrained by other, more reliable dating methods. Blake (1991) provided a detailed correlation of benthic foram stages with radiometric dates, siliceous microfossils, calcareous nannofossils, and planktonic foraminifers in the Los Angeles basin (Fig. 1.2). Blake's (1991) age estimates of strata in the Los Angeles basin are indicated on Figure 1.3. In the Ventura basin, correlation of ashes (based on chemical fingerprinting) has been useful in dating Plio-Pleistocene strata (Sarna-Wojcicki et al., 1984, 1991), but similar studies are in their infancy in the Los Angeles basin. Los Angeles basin strata cannot be calibrated reliably to the ash dates from the Ventura basin because the Plio-Pleistocene may be too provincial (Yeats, 1978) to allow correlation between basins.

Correlation of diatoms is the most reliable method of dating and correlating middle Miocene and Pliocene strata in California (Barron, 1986). Unfortunately, core samples from the oil industry have not been used for systematic diatom identification and correlation in the Los Angeles basin. Outcropping Delmontian strata in the Los Angeles basin include subzones a and b of the diatom *Nitzschia reinholdii* (at Topanga Canyon and Malaga Cove: T and M on Fig. 1.2). At Newport Bay (N, Fig. 1.2), subzone b is within Delmontian strata, but subzone a is within uppermost Mohnian strata. The age of subzone a is 6.7 - 6.1 m.y., and subzone b is 6.1 - 5.1 m.y. (Blake, 1991), making the Delmontian - Repettian contact younger than 5.1 Ma at all three localities. Samples from Los Angeles Metro Rail borings (northern Los Angeles basin) also contain diatoms from *N. reinholdii* subzones a and b (J. Barron, unpublished data; Ponti et al., 1993). A discussion of these samples is presented in Chapter 4.

The age of the Delmontian - Repettian contact is constrained at Malaga Cove (M on Fig. 1.2), where the Lawlor Tuff, dated at 4.42 ±0.57 Ma (Obradovich and Naeser, 1981), occurs in the Delmontian Malaga Mudstone. In the San Francisco bay area, the Lawlor Tuff is dated by the K-Ar method at 4.1 ±0.2 Ma (Sarna-Wojcicki et al., 1991). The Lawlor Tuff occurs within a diatom assemblage zone that ranges from 5.1 to 3.6 Ma (Blake, 1991). The Delmontian Malaga Mudstone also contains radiolarian datums at 5.2 and 4.8 Ma, and a planktonic foraminiferal coiling shift at 4.6 to 4.2 Ma (Blake, 1991). Near the base of the unconformably-overlying middle Repettian benthic foram stage is another ash bed, the Nomlaki Tuff, with a zircon fission-track date of 3.4 ±0.3 Ma (Obradovich and Naeser, 1981; Sarna-Wojcicki et al.,...
The Nolmlaki Tuff has also been reported in Repettian cores from oil wells in the Los Angeles basin (T. McCulloh, written comm. in Sarna-Wojcicki et al., 1991). At Malaga Cove, a radiolarian datum (3.2 Ma) and a planktonic foraminiferal coiling shift (2.5 - 2.4 Ma) occur within the middle Repettian strata (Blake, 1991). These data indicate that the Delmontian - Repettian contact is between 4.2 and 3.4 Ma, but much closer to the older age because of the unconformity with missing lower Repettian strata.

At Newport Bay (N on Fig. 1.2), the 5.2 Ma radiolarian datum (mentioned above) falls in the Delmontian benthic foram stage, but the 4.8 Ma radiolarian datum occurs in the Repettian benthic foram stage (Blake, 1991). The Delmontian - Repettian contact is therefore between 5.2 and 4.8 Ma, or about 1 m.y. older than at Malaga Cove. The Repettian - Venturian (Repetto - Pico) contact is younger than the 3.2 Ma radiolarian datum, and at the base of the 2.5 - 2.4 Ma planktonic foraminiferal coiling shift, giving a date of ~2.5 Ma (Blake, 1991). The Venturian - Wheelerian contact (lower Pico - middle Pico) is younger than a planktonic foraminiferal coiling shift (2.1 - 1.8 Ma), and slightly older than a 1.7 Ma radiolarian datum (Blake, 1991).

In the Repetto Hills (R on Fig. 1.2), Repettian strata are exposed, but not the underlying Delmontian or overlying Pico (Venturian) strata. Here, the 4.8 Ma radiolarian datum and the 4.6 - 4.2 Ma planktonic foraminiferal coiling shift occur within the lower Repettian, placing the base of the Repettian at ≥4.8 Ma, similar to the age of the Repettian strata at Newport Bay (Blake, 1991). The Repetto Hills upper Repettian includes the 3.2 Ma radiolarian datum, indicating that the upper Repettian of Repetto Hills and Newport Bay is older than at Malaga Cove, where the 3.2 Ma radiolarian datum, and the 2.5 - 2.4 Ma planktonic foraminiferal coiling shift occur in the middle Repettian (Blake, 1991).

Despite these discrepancies, Wright (1991) reported that a distinctive bentonite, noted on electric logs in various parts of the Los Angeles basin (including the Whittier and Inglewood oil fields), occurs just below the Delmontian - Repettian boundary. The consistent stratigraphic location of the bentonite suggests that the Delmontian - Repettian boundary is approximately synchronous around the basin (Wright, 1991).

Use of benthic foram stages in this study

In this study, we are forced to rely on benthic foram stages due to the lack of other kinds of paleontologic or age data. We follow Blake (1991; Fig. 1.3) in assigning
approximate ages to stratigraphic horizons. Where possible, correlation of strata is based on lithology (as expressed on an electric log). Where electric logs cannot be correlated, benthic foram stages must be used. Details of the correlation methods used in this study are presented in Chapter 3.
CHAPTER 2: QUATERNARY STRATIGRAPHY AND STRUCTURES

INTRODUCTION

The southern range front of the Santa Monica Mountains, marked by the active Santa Monica - Hollywood - Raymond Hill fault system (Figs. 1.1 and 2.1), has long been regarded as the southern boundary of the west-trending Transverse Ranges. However, the 1987 Whittier Narrows earthquake (M_w = 5.9; Hauksson, 1988) occurred south of this boundary (Fig. 1.1), on a previously-unrecognized zone of blind reverse faults and folds (Davis et al., 1989; Hauksson, 1990; Bullard and Lettis, 1993) beneath the densely-populated lowlands of northern Los Angeles. These blind faults pose a significant earthquake hazard, but the Alquist Priolo Special Studies Zones Act (State of California, 1972), which requires detailed zoning studies prior to development near faults with Holocene surface rupture, does not apply because blind faults do not rupture the surface. An increased earthquake danger for this area is suggested by long-term slip rates that are higher than the last two centuries of seismic release can account for, suggesting a slip deficit that may be made up by future earthquakes (Davis et al., 1989; Lin and Stein, 1989). Similarly, Hauksson (1992) noted a large deficit in historic seismic moment release compared to accumulating seismic moment on blind faults in the Los Angeles area.

In this study, subsurface mapping of Quaternary gravels documents the latest phase of deformation in the northern Los Angeles basin, which includes the Wilshire arch and its underlying blind thrust fault. The Wilshire fault, lying beneath Hollywood and Beverly Hills, poses a seismic hazard to some of the most expensive real estate in the world.
Figure 2.1. Structure-contour map on the base of the Quaternary marine gravels (Qmg); location shown on Figure 1.1. Contour interval is 50 m. Data from Los Angeles Metro Rail borings are from Converse Consultants, Inc. (Pasadena). Stippled areas are topographic fault scarps from Dolan and Sieh (1992). Double lines are minor folds in the Quaternary alluvium (Qal) (from Dolan and Sieh, 1992). Qmg is overlapped by Qal east of the dash-dot line (estimated from Eckis, 1934; CDWR, 1961; and Metro Rail data). Dashed contours at the eastern end of the Hollywood basin are estimated from groundwater studies (Eckis, 1934; CDWR, 1961). The approximate location of the North Salt Lake fault (NSLF) is shown, with a tick mark indicating the dip direction of the fault. West of the Newport-Inglewood fault (NIF), the southern range front of the Santa Monica Mountains is marked by the dashed line just north of Sunset Blvd. Locations of cross sections A-A', F-F', and G-G' are shown.
QUATERNARY STRATIGRAPHY

Quaternary marine sand and gravel (referred to here as Qmg) of the Los Angeles basin have been identified in outcrops (e.g. Tieje, 1926; Hoots, 1931; Woodring et al., 1946; Rodda, 1957), in groundwater studies (Eckis, 1934; Poland et al., 1956, 1959; California Department of Water Resources [CDWR], 1961), and in exploratory borings for the Los Angeles subway system (unpublished geotechnical reports, Converse Consultants, Inc., Pasadena, CA). These Quaternary strata have been classified as lower Pleistocene San Pedro Formation overlain unconformably by upper Pleistocene Palos Verdes Formation (Fig. 2.2a). The type localities of the San Pedro and Palos Verdes Formations, which are in the Palos Verdes area (PVH on Fig. 1.1), were described by Woodring et al. (1946), who noted that the two formations may be time-transgressive and indistinguishable based on faunal evidence.

Ponti (1989) defined amino-acid assemblage zones and correlated them to the oxygen-isotope time scale for the Pleistocene type sections and for the Pleistocene aquifers of Poland et al. (1956, 1959) and CDWR (1961) in the southwestern Los Angeles basin. Ponti (1989) determined that the type section of the San Pedro Formation was deposited ~0.3 - ~0.45 Ma, which is significantly younger than the previously-assumed early Pleistocene age (Fig. 2.2b). In the southwestern Los Angeles basin, samples from the subsurface deposits called San Pedro Formation, however, are early Pleistocene (~0.61 - >0.8 Ma; Ponti, 1989), indicating that two different deposits have been referred to as the San Pedro Formation (Fig. 2.2). The subsurface sample was above the base of the subsurface San Pedro Formation, indicating that the base of the San Pedro Formation was deposited >0.8 Ma.

In the northern Los Angeles basin, Qmg mapped in this study has not been dated, and field studies are limited by urbanization. Qmg is probably correlative to the subsurface San Pedro Formation, not to the younger type-section San Pedro Formation (D. Ponti, pers. comm., 1992). Qmg may be time-transgressive between the study area and the subsurface strata dated by Ponti (1989). The underlying uppermost Pico strata have not been dated, but their age is estimated, by correlation of microfossils, at approximately 1.0 Ma (Blake, 1991). Therefore, the age of the base of Qmg in the study area is estimated at 0.8 - 1.0 Ma.
Figure 2.2. Quaternary stratigraphy of the Los Angeles basin. (a) Traditional classification of Quaternary stratigraphy of the Los Angeles basin from studies of outcrops and subsurface units. (b) Quaternary stratigraphy of the southwestern LA basin, from correlation of surface and subsurface strata based on aminostratigraphy and the oxygen-isotope timescale (Ponti 1989).
METHODS

In the northern Los Angeles basin, the youngest stratigraphic horizon that can be correlated by subsurface mapping is the base of Qmg, which was correlated in 72 oil wells using electric logs as the primary data source (Fig. 2.3). In addition, nine water wells with electric logs in the Santa Monica area (provided by Robert L. Hill, Calif. Div. Mines & Geology, Los Angeles) and three water wells with electric logs in the City of Beverly Hills (Sec. 32, Twp. 1S, Rge. 14) were used to map the base of Qmg.

The base of Qmg (dotted line, Fig. 2.3) is defined here as the base of the consistently coarse-grained sequence, rather than the base of the lowest coarse-grained bed. For most oil wells used in this study, oil companies have assigned some intervals to benthic foram stages. These correlations are useful for identifying major unconformities, for example where Miocene (Mohnian Stage) strata are directly overlain by Qmg (e.g. PE CH-1 and Laurel CH-2; Fig. 2.3), resulting in an abrupt character change in the electric log. Farther south, the contact between the upper Pico and the overlying Qmg is gradational and coarsening upward, resulting in a funnel shape on the electric log (e.g. Packard CH-1 and Adamson CH-1; Fig. 2.3). The upper Pico - Qmg contact represents a shallowing of water depth, which resulted in the lithologic change from upper bathyal fine-grained strata to shallow-marine coarse-grained strata.

Interpreting Quaternary deformation of the base of Qmg (Fig. 2.1) assumes that this horizon was originally near-horizontal, and not time-transgressive in the study area. In most of the study area, the contact between Qmg and upper Pico marine strata is gradational and conformable, suggesting that this contact had little relief. Where Qmg rests unconformably on older formations, there is no evidence of relief or subaerial exposure at the unconformity, which probably formed on an inner continental-shelf wave-cut platform, resulting in a near-horizontal erosional surface. Qmg deposited on the unconformity would also have been nearly flat-lying. Poland et al. (1959) stated that the (probably) equivalent subsurface San Pedro Formation was deposited in coastal deltas, fed by alluvial fans from the Santa Monica and San Gabriel mountains, and modified by longshore currents. Multiple alluvial-fan point sources would approximate a line source, resulting in deposition of flat-lying gravel sheets rather than channelized deposits. At present, it is not possible to determine whether the base of Qmg represents a time-line, but this is a reasonable conjecture for the small study area (~100 km²).
Figure 2.3. Vertically-exaggerated cross section G-G' (location on Fig. 2.1) showing the appearance and correlation, by electric logs, of the base of the Quaternary marine gravels (Qmg). The base of Qmg is indicated by the dotted line. To the south, Qmg rests conformably on Plio-Pleistocene Pico strata, resulting in the funnel-shaped, gradational contact seen on the electric logs. To the north, there is an unconformity (wavy line) between Qmg and the late Miocene middle/lower Puente Formation (Mohnian Stage), resulting in the sharper contact seen on the electric logs of Laurel CH-2 and PE CH-1.
D.J. Ponti (pers. comm., 1992) suggested that the base of Qmg may approximate a
time-line, and the change to gravel deposition may have resulted from a regional
(probably climatic) influence.
THE WILSHIRE ARCH

Figure 2.1 is a structure contour map on the base of Qmg, showing the location of data used in this study. The base of Qmg is warped into the Wilshire arch, a broad, west-plunging anticline with its axis parallel to Wilshire Boulevard, that terminates at the Newport-Inglewood fault. This structural high is also present on maps of the base of the Quaternary aquifers by Eckis (1934) and CDWR (1961). Thinning of Qmg over the Wilshire arch (Figs. 2.4 and 2.5), by onlap and/or erosion, was caused by uplift of the arch during and after deposition of Qmg. The part of the Wilshire arch that lies east of the dotted line on Figure 2.1 is a region where Qmg is overlapped by late Quaternary alluvium (Qal) (interpreted from: Eckis, 1934; CDWR, 1961; Metro Rail data from Converse Consultants, Inc., Pasadena), which rests directly on late Miocene strata.

Recent deformation of the Wilshire arch is evidenced by gentle folds in the Qal overlying the Wilshire arch. Qal is warped into several minor south-vergent, WNW-trending anticlines (double lines, Fig. 2.1) which are apparently secondary compressive structures on the Wilshire arch (Dolan and Sieh, 1992).

Present-day deformation of the Wilshire arch is suggested by leveling data from 1925 - 1938 (Grant and Sheppard, 1939) and 1949 - 1970 (Ledingham, 1975). Figure 2.6 shows contoured leveling data from 1949 - 1960 (in red; simplified from Ledingham, 1975), with simplified structure contours on the base of Qmg for reference (in black; from Figure 2.1). The simplest observation that can be made from the leveling data (red; Fig. 2.6) is that (slight) net uplift occurred on the crest of the Wilshire arch from 1949 - 1960, with net subsidence in the approximate positions of the Hollywood basin and central trough (also documented by Grant and Sheppard, 1939). The general alignment of the present-day (red) and Quaternary (black) features suggests that the Quaternary folds are active today. Subsidence in the Los Angeles basin can be caused by tectonic/structural features, oil production, and/or groundwater removal. Grant and Sheppard (1939), Ledingham (1975), and Castle and Yerkes (1976) concluded that tectonic forces are partly to primarily responsible for subsidence in the Hollywood basin and central trough. Because leveling data can provide independent evidence of active tectonics, an important future task is analysis of leveling data in the northern Los Angeles basin from the last 20 years. This is especially important because oil production has decreased and groundwater removal has completely ceased within the last ~20 years.
Figure 2.4. Cross section F-F' across the Wilshire arch and Las Cienegas fault (location shown on Fig. 2.1). This figure is a reduced version of Plate 7. Formation dips on wells are from dipmeter data (single tick marks) and core dips (double dip symbol). The inset shows details of the unconformable contact between the Quaternary marine gravels (Qmg, diagonal lines) and the underlying Pico strata, showing that uplift on the Wilshire arch occurred after deposition of the middle Pico, and after deposition of part or all of the upper Pico. Fault abbreviations are: HF = Hollywood fault; LCF = Las Cienegas fault; SVF = San Vicente fault. Stratigraphy abbreviations: P = Pico; R = Repetto; D = Delmontian; UM = Upper Mohnian; LM = Lower Mohnian. SMM = Santa Monica Mountains.
Figure 2.5. Cross section A-A' across the Wilshire arch (location on Fig. 2.1), also showing possible locations of the Wilshire fault, and showing underlying Tertiary structures. This figure is a simplified version of Plate 2. Contacts queried where inferred. For the Hollywood fault, which has reverse-left oblique slip, T = toward and A = away. Arrows indicate relative motion on faults. Tick marks on wells represent dipmeter data. Abbreviations are: Qmg = Quaternary marine gravels (diagonal-lined pattern); Qal = Quaternary alluvium; SL = sea level. Shaded area represents approximate location of the north-dipping zone of microearthquakes that may have occurred on the Wilshire fault; error bars on earthquake locations are omitted for simplicity, but are shown on Figure 2.8. Dash-dot line I shows the fault-ramp location as determined by a geometric fault-bend fold model (based on Suppe, 1983). Dash-dot line II shows the fault location as determined by elastic dislocation modeling.
Figure 2.6. Comparison of long- and short-term deformation of the Wilshire arch, Hollywood basin (HB), and central trough. Long-term deformation is shown in black structure contours on the base of the Quaternary marine gravels (Qmg) over the last ~1 m.y. (from Fig. 2.1). Deformation between 1949 and 1960 is shown by the red contours of subsidence (simplified from Ledingham, 1975). BH = Baldwin Hills; HB = Hollywood basin; HF = Hollywood fault; MPF = MacArthur Park fault; NIF = Newport-Inglewood fault.
Miocene strata lie beneath Qal on the crest of the Wilshire arch, with progressively younger strata lying farther south (Fig. 2.4; reduced version of Plate 7). Upper Pico strata subcrop farther south than middle/lower Pico strata. Middle/lower Pico strata do not thin to the north between the Texam U-19-1 well and wells along strike from Union CH-29 (Fig. 2.4, inset), indicating that the middle/lower Pico strata were deposited prior to any uplift on the Wilshire arch. Uplift may have begun as early as during deposition of the upper Pico, which may have partially onlapped onto the south side of the Wilshire arch. Ideally, dip data would allow for the differentiation between thinning of the upper Pico due to onlap (thinning during deposition) and thinning due to erosion (thinning after deposition). Unfortunately, available dip data do not permit the resolution of this question. Uplift of the Wilshire arch therefore occurred primarily after deposition of the Pico Member of the Fernando Formation, and caused erosion of the Fernando and Puente Formations. These relationships can also be seen on other cross sections, shown on Plates 2 (Fig. 2.5 is a reduced version), 3, 4, 5, 6 and 7 (Fig. 2.4 is a reduced version).

The Wilshire arch cannot be traced east into a series of low hills just southwest of the Hollywood Freeway (Fig. 2.1). The southwest edge of the hills is marked by a set of NW-trending topographic scarps associated with the potentially active MacArthur Park fault (Dolan and Sieh, 1992; Dolan et al., 1992). The MacArthur Park fault juxtaposes middle Puente Formation west of this fault (determined in this study) against upper Puente Formation east of the fault (Dibblee, 1991).
THE WILSHIRE FAULT

An important feature of the Wilshire arch is the blind thrust fault that is underlying and causing the Wilshire arch. The earthquake potential of this blind thrust is substantiated by the 1987 Whittier Narrows earthquake ($M_L = 5.9$; Hauksson et al., 1988; Fig. 1.1) on a similar structure ~20 km east of the study area. This earthquake probably occurred on the south-vergent Elysian Park blind thrust of Davis et al. (1989), which is south of the southernmost major reverse fault of the Transverse Ranges (the Raymond Hill fault on Fig. 1.1). The proposed blind thrust underlying and causing the Wilshire arch may be analogous to the Elysian Park thrust.

Fault-bend fold model

The Wilshire arch is modeled as a fold underlain and caused by the blind, north-dipping Wilshire thrust fault. Using a non-elastic fault-bend fold model (Suppe, 1983), the fault ramp can be reconstructed with a dip of 10 - 15° north (Fig. 2.5), with the fault ramp constrained by oil wells to be ≥3.5 km deep. In the fault-bend fold model, the Wilshire arch is formed by 1.5 km of dip slip in the last 0.8 - 1.0 m.y., which gives a dip-slip rate of 1.5 - 1.9 mm/year. See Schneider (1994) for additional details about the fault-bend fold model of the Wilshire fault.

Microearthquakes

Earthquake data, recorded 1932 - 1992 by the CalTech/USGS network (Pasadena, CA), were acquired for the Beverly Hills and Hollywood 7.5 minute quadrangles. 228 earthquakes, with a maximum magnitude of 4.0, were recorded in the two-quadrangle study area during the 61-year period. Figure 2.7 shows the A- and B-quality events for the study area (central area of Fig. 2.7), with an additional 7.5 minute quadrangle on each side, for a regional perspective. "A" events have a horizontal error of ± 1 km and vertical error of ± 2 km; "B" events have a horizontal of error ± 2 km and vertical error of ± 5 km. From the pattern of earthquakes (Fig. 2.7), it is clear that the Los Angeles basin has more seismically active faults than the Santa Monica Mountains
Figure 2.7. Seismicity of the northern Los Angeles basin (1932 - 1992). Only events of quality A and B are shown. Depth and magnitude of events are indicated by ellipticity and size of circle, respectively. In the study area (center of map), structure contours on the base of the Quaternary marine gravels (from Fig. 2.1) are shown for reference. H-H' is an 8 km wide swath across the Wilshire arch, whose earthquakes are shown in cross section view on Figure 2.5 and Figure 2.8. Events 1 - 6 are the six earthquakes that may define the Wilshire fault. Abbreviations are: BH = Baldwin Hills; N-I ft. = Newport-INGLEwood fault (SSE of Baldwin Hills).
Figure 2.8. Cross section H-H', showing seismicity (quality A and B events only) of an 8 km wide swath that crosses the Wilshire arch. Location of cross section shown H-H' is shown on Figure 2.7. Abbreviations are: BH = Baldwin Hills, CT = central trough; HB = Hollywood basin; NSLF = North Salt Lake fault; SMM = Santa Monica Mountains; WA = Wilshire arch. Length of line indicates relative magnitude of earthquakes. Events 1 - 6 are the six earthquakes that may define the Wilshire fault; these events are shown in map view on Figure 2.7. The best-fit fault has an apparent dip of ~30° to the north, on this north-south cross section. The cluster of earthquakes south of the study area is associated with the Newport-Inglewood fault.
to the north. Even the active Santa Monica - Hollywood fault system, dipping north under the Santa Monica Mountains, is largely aseismic for 1932 - 1992. The Newport-Inglewood fault, however, is marked by a cluster of microseismicity extending southeast from the Baldwin Hills (BH, Fig. 2.7). The seismicity associated with the Newport-Inglewood fault is also apparent on the cross section of seismicity that crosses the Wilshire arch (H - H'; Fig. 2.8).

A zone of six small earthquakes (map view: Fig. 2.7, #'s 1 - 6), recorded 1976 - 1991, dips 30 - 35° north under the Wilshire arch (cross section view, with error bars: Fig. 2.8). These six events have magnitudes 1.9 - 2.3, with the shallowest event at 2.8 ± 2 km depth. The zone of earthquakes, shown in cross section view (Fig. 2.6), may illuminate the Wilshire fault, suggesting a steeper dip for the Wilshire fault than determined by the fault-bend fold method. Focal mechanisms (E. Hauksson, pers. comm., 1993) for the six events are inconclusive. The apparent alignment of events at exactly 8.00 km depth (Fig. 2.8) is an artifact in the USGS-Caltech processing. The real depth of these events is close, but not equal to, 8.00 km.

**Elastic dislocation model**

Another method of locating the Wilshire fault uses an elastic-dislocation model, which involves inverse modeling of the wavelength (10 km) and amplitude (400 m) of the Wilshire arch (Table 2.1). A detailed discussion of the elastic dislocation modeling of the Wilshire fault can be found in Schneider, 1994. King et al. (1988) showed that the wavelength of a fold associated with an active fault is comparable to the wavelength of coseismic folding. Furthermore, Lin and Stein (1989) suggested that folds grow dominantly by coseismic deformation. Therefore, we assume that the Wilshire arch represents the cumulative coseismic folding over the past 0.8-1.0 m.y. We model the Wilshire arch as deformation of a free surface, caused by slip on a fault embedded in an elastic half space. Because the Wilshire fault has had no large historic earthquakes, we have no direct measurement of coseismic slip for the elastic-dislocation model. Therefore, we use 1.0 m, which was the coseismic slip during the 1987 Whittier Narrows earthquake (Lin and Stein, 1989) on the analogous Elysian Park blind thrust named by Davis et al. (1989).

In a three-dimensional elastic-dislocation model, the fault must dip ≥30°, and the fault tip must be buried at a depth of 2.0-2.8 km, to reproduce the observed
wavelength of the Wilshire arch. Well data (Fig. 2.5) indicate that the fault tip is ≥ 2.5 km deep. We use a burial depth of 2.8 km to be most compatible with the seismicity and with the fault-bend fold model. The best-fit modeled fault (Fig. 2.9) dips 35° toward N15°E, which is consistent with the 30°-35° dip of seismicity. Right-reverse oblique slip (0.67 m reverse slip and 0.74 m right slip, adding to 1.0 m coseismic oblique slip; Table 2.1), is required to reproduce the Wilshire arch, Hollywood basin, and central trough in their correct positions (Fig. 2.9). The orientation of the fault is consistent with right-reverse oblique faulting in a stress field where the maximum horizontal stress (σ1) is north to north-northeast (Hauksson, 1990; Mount and Suppe, 1992). The 400 m amplitude of the Wilshire arch could have formed by about 2600 one-meter oblique-slip earthquakes of the type modeled in Figure 2.9, each producing an amplitude of 0.156 m. According to this model, 2.6 km of right-reverse oblique slip has occurred on the best-fit Wilshire fault over the past 0.8-1.0 m.y., yielding a slip rate of 2.6-3.2 mm/yr. The right-slip component suggests that right slip on the Whittier fault (Fig. 1.2) may be transferred in part to the zone of blind thrusts extending west to the Wilshire fault.

Table 2.1. Best-fit, three-dimensional elastic dislocation model.

<table>
<thead>
<tr>
<th>parameter</th>
<th>1 modeled event (Fig. 2.9)</th>
<th>~2600 events (0.8 - 1.0 Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>reverse slip</td>
<td>0.67 m</td>
<td>1.7 km</td>
</tr>
<tr>
<td>right slip</td>
<td>0.74 m</td>
<td>1.9 km</td>
</tr>
<tr>
<td>net slip</td>
<td>1.0 m</td>
<td>2.6 km</td>
</tr>
<tr>
<td>fold amplitude</td>
<td>0.156 m*</td>
<td>400 m†</td>
</tr>
<tr>
<td>fold wavelength</td>
<td>10 km†</td>
<td>10 km†</td>
</tr>
</tbody>
</table>

* from three-dimensional elastic dislocation model (Fig. 2.9)
† from subsurface correlation of geology (Fig. 2.1)
Figure 2.9. Three-dimensional elastic-dislocation model of the Wilshire fault. Deformation of a free surface is caused by an underlying fault within a three-dimensional elastic half space. Deformation shown here results from 1.0 m of right-reverse oblique slip, with a reverse-slip component of 0.67 m and right slip component of 0.74 m (Table 2.1). Total fold amplitude is 156 mm. Contour interval is 25 mm, with supplemental (dashed) contours at 10 mm intervals in the Hollywood basin. Right-reverse slip on the modeled Wilshire fault produces relative subsidence in the position of the Hollywood basin and central trough. Ticks are on the inside of contours of subsidence. $\sigma_1$ shows the approximate direction of maximum horizontal stress (Hauksson, 1990; Mount and Suppe, 1992). Width is measured down dip on the fault plane; length is measured along strike; depth is burial depth of the fault tip.
Possible Wilshire fault earthquake

Using the fault parameters of the best-fit dislocation model (Table 2.1, Fig. 2.9), we can estimate the seismic hazard associated with the blind Wilshire fault. The moment magnitude ($M_W$) of a possible Wilshire fault earthquake is 5.7, based on

$$M_W = \frac{2}{3} \log M_o - 10.7,$$

where $M_o = \mu u A$, $\mu$ = shear modulus of elasticity ($3 \times 10^{11}$ dyne/cm$^2$), $u$ = slip, and $A$ = area of slip (Hanks and Kanamori, 1979). For our calculation, $u = 1.0$ m (from the analogous 1987 Whittier Narrows earthquake; Lin and Stein, 1989); $A = 16.2$ km$^2$ (Fig. 2.9, width times length). An earthquake of $M_W = 5.7$ could cause significant property damage in this densely populated area. This magnitude is a minimum, assuming an earthquake ruptures the Wilshire fault only, limited to the west by the Newport-Inglewood fault (Hauksson, 1990) and to the east by the MacArthur Park fault. If an earthquake ruptures more than one segment, as documented for several large reverse-slip earthquakes (Changma, China, 1932 - Meyer, 1991 and Peltzer et al., 1988; El Asnam, Algeria, 1980 - Yielding et al., 1981; Spitak, Armenia, 1988 - Haessler et al., 1992), the magnitude of the earthquake, the property damage, and the potential for loss of life would be increased substantially. The newly identified Wilshire fault poses a significant, previously unrecognized seismic hazard to Hollywood, Beverly Hills, and adjacent districts of downtown Los Angeles.
OTHER QUATERNARY STRUCTURES OF THE
NORTHERN LOS ANGELES BASIN

Hollywood basin

Northwest of the Wilshire arch is the Hollywood basin (Fig. 2.1), an active syncline containing up to 350 - 400 m of Qmg and Qal (Laurel CH-2; Fig. 2.3 and Fig. 2.5). The Hollywood basin has an ENE trend, parallel to the active Hollywood fault, but discordant with the south flank of the Wilshire arch (Fig. 2.1). The Hollywood basin was identified as a groundwater basin by Eckis (1934) and CDWR (1961). Structure contours have been interpreted from Eckis (1934) and CDWR (1961) and added to Figure 2.1 in the eastern part of the Hollywood basin (dashed contours), where there are no oil wells. In the Hollywood basin, Qmg overlies Pliocene strata (Hollywood CH-1, Fig. 2.4) or Miocene strata (Laurel CH-2, Fig. 2.5). The southeast part of the Hollywood basin may be influenced by the north-dipping North Salt Lake fault (Wright, 1991), which has normal separation in cross-section view (Fig. 2.4), but may have a left-lateral strike-slip history. The North Salt Lake fault cuts Pliocene strata, but there is no evidence that it was active during the Quaternary. Unfortunately, there are not enough data in the Hollywood basin to fully resolve the Quaternary role of the North Salt Lake fault.

Santa Monica - Hollywood fault system

West of the Newport-Inglewood fault is the Santa Monica fault, whose active trace is marked by topographic scarps (Crook et al., 1983; Dolan and Sieh, 1991; Wright 1991; shown on Fig. 2.1 from Dolan and Sieh, 1992). The structure-contour map on the base of Qmg (Fig. 2.1) defines a SSE-dipping monocline, parallel to the fault scarps at the 0 to +50 m structure contours, and associated with the active Santa Monica fault. East of the Newport-Inglewood fault, the mountain front of the Santa Monica Mountains has linear, topographic scarps and active fan deposition, indicating recent, rapid uplift on this part of the Hollywood fault (Crook et al., 1983; Dolan and Sieh, 1991, 1992). West of the Newport-Inglewood fault, however, the mountain front is characterized by dissected, segmented fans and no topographic fault scarps,
indicating a lack of recent uplift on this possible western extension of the Hollywood fault (Fig. 2.1) (Crook et al., 1983; Dolan and Sieh, 1991, 1992). Dolan and Sieh (1991, 1992) and Wright (1991) concluded that the Santa Monica fault, and not the possible western extension of the Hollywood fault, is active west of the Newport-Inglewood fault. Hoots (1931) recognized that the Hollywood fault east of the Newport-Inglewood fault was active more recently than the possible western extension of the Hollywood fault. The northern extension of the Newport-Inglewood fault terminates against the Hollywood fault and accommodates a left step between the active Santa Monica and Hollywood faults (Fig. 2.1; Dolan and Sieh, 1991; Wright, 1991).

**Newport-Inglewood fault**

The Baldwin Hills (Fig. 2.1) are the northernmost unequivocal topographic expression of the Newport-Inglewood fault. To the north, a possible surface trace of the Newport-Inglewood fault has been identified by a NNW-trending topographic lineament (Poland et al., 1959; Dolan and Sieh, 1991; Wright, 1991; shown on Fig. 2.1 from Dolan and Sieh, 1992). This northern trace of the Newport-Inglewood fault is coincident with a boundary between different Quaternary structures: to the west is the active Santa Monica fault; to the east are the active Hollywood fault, Hollywood basin, Wilshire arch, and central trough. Additionally, west of the Newport-Inglewood fault, the Santa Monica fault is the active, south-vergent thrust fault, and the possible mountain-front Hollywood fault does not appear to be active. East of the Newport-Inglewood fault the Hollywood fault is an active range-front fault with the Hollywood basin in the footwall block. All these features terminate at the Newport-Inglewood fault, suggesting that the Newport-Inglewood fault is a structural boundary.
CHAPTER 3: DATA SOURCES, DATA FORMAT, AND METHODS

INTRODUCTION

This chapter describes the origin and format of the data used in this study, and the methods by which the data were analyzed. The results and interpretation of the data are presented in Chapter 4. The primary data used in this study were oil well data, most of which were provided by Chevron U.S.A. Inc. (Bakersfield, CA) and Unocal Corporation (Santa Fe Springs, CA). Additional oil well data were purchased from the following sources: California Division of Oil and Gas (CDOG, Long Beach, CA), Riley Electric Log Inc. (Oklahoma City, OK), Petroleum Information (Denver, CO), and M.J. Systems Inc. (Denver, CO). The well files generally include data necessary in this study (electric log, history, directional survey for deviated wells). Some wells also include dip data and paleontologic data, which were also essential to the project, and mud log, sample descriptions, etc., which were helpful in some instances. Most of the wells are directionally drilled, requiring calculation of X, Y, and Z coordinates. Plate 1 lists the drillpads and the wildcat wells used in this study.
CORRELATION OF STRATA IN OIL WELLS

Electric logs

In this study, the most important component of the oil well file is the electric log. The electric log displays spontaneous potential and resistivity curves, which are used for correlating strata. Spontaneous potential, measured in millivolts, measures the electrical potential (voltage) between the strata, its formation water, and the drilling mud. When water conductivity is greater than mud conductivity, sandstone (with high porosity/permeability) has low spontaneous potential, and shale (with low permeability) has high spontaneous potential. Resistivity, measured in ohms-m²/m, measures the ability of strata (and the fluids within) to impede the flow of an electrical current. Low resistivity indicates high porosity, conductive interstitial fluid (saline water), or shale. High resistivity indicates strata that are dry, or invaded with a non-conducting fluid (oil or pure water). Taken together, the spontaneous potential and resistivity curves form a pattern that allows for differentiation between shale and sandstone.

Correlation of electric logs, where possible, was the most reliable method of mapping subsurface strata in the northern Los Angeles basin. A stratigraphic horizon, correlated from well to well, is interpreted to represent a time line, because most of the Pliocene deposition in the northern Los Angeles basin was by turbidites, which deposit a fining-upwards sequence almost instantaneously over a large area. Bentonites, where present, provide the most reliable correlation of electric logs, because they represent an unambiguous timeline. In the East Beverly Hills area, several small bentonites occur in the upper Repetto and one occurs in the lower Repetto, but none is widespread enough to be used as a timeline throughout the entire study area. Shales are fairly reliable for correlation because their fine-grained sediments were deposited relatively uniformly over topographic highs and lows. Sandstones, especially in Repetto strata, tend to thin or disappear over highs (e.g. an active anticline), and thicken/coarsen in lows (e.g. an active syncline), and may not maintain a characteristic form from well to well.

Several other circumstances can complicate the use of electric logs. For some wells, electric logs were not run in the top 2000 - 6000 ft (610 - 1830 m) well depth, which generally includes the Pliocene section. The few well files entirely missing an electric log were not used unless the well had useful paleontological data. Many wells at the San Vicente pad (Sec. 20, Twp. 1S, Rge. 14W), and several at other drillpads,
were drilled nearly parallel to bedding (Fig. 3.1a), making identification of specific features nearly impossible. For many San Vicente wells, this problem was aggravated by a lack of reliable paleontologic data. A similar problem occurs if a well is drilled in the downdip direction, first steeper than bedding, then shallower than bedding (Fig. 3.1b). Thus the well penetrates progressively older strata, then progressively younger strata. Examples of this phenomenon occur in PE-4-OH on cross section D-D' (Plate 5), and Murphy 8-OH on cross section F-F' (Plate 7). Despite their complex geometries, both wells provide important constraints because of the paleontological and dipmeter data present.

**Paleontology**

The primary paleontological data used in this study are benthic forams, assigned to stages by oil companies. When not otherwise specified, the term "paleo" refers to benthic foram data. Many well files have little or no paleo, but all drillpads and most wildcat (interfield) wells have some paleo. In some cases, however, the paleo is limited to the Repetto or Miocene producing zones. The format of the paleo varies: some well files list all samples and all species present, but in most cases, the species are encoded by industry abbreviations. Other wells have stage assignments or stage tops indicated but no specific samples listed. The industry paleo assignments were used in this study, except in cases where there was a discrepancy between the paleo and other data sources.

Planning and construction of the Los Angeles Metro Rail produced additional shallow data, including paleo, in the northeast quadrant of the study area. Lithologic logs, maps, cross sections, reports, electric logs, and samples were provided for this project by Converse Consultants West (Pasadena, CA), Parsons Brinckerhoff Quade & Douglas, Inc. (Orange, CA), and Metro Rail Transit Consultants (Los Angeles, CA). Benthic forams from Metro Rail borings were identified and assigned to stages by Mary Lou Cotton (Bakersfield, CA), and confirmed by Kris McDougall (USGS, Menlo Park, CA). The Metro Rail samples also contain diatoms whose ages are interpreted by John Barron (USGS, Menlo Park, CA), ashes correlated by Andrei Sarna-Wojcicki (USGS, Menlo Park, CA), and glass (from ashes) for fission-track dating by Nancy Naeser (USGS, Denver).
Figure 3.1. Two examples of bedding/well course geometries that can make well correlation difficult. (a) Part of the well course is nearly parallel to bedding. (b) Well penetrates progressively older, then progressively younger strata.
Method of correlation of oil wells

Correlating a group of wells, either within one drillsite or between sites, involved the following procedure. (1) Identify all wells in the group with Pliocene and/or uppermost Miocene paleo. Between 5% and 65% of the wells at each drillsite have at least one Pliocene paleo pick. (2) Correlate the electric logs of the wells that have paleo, and compile the paleo onto one electric log for each drillsite. (3) Add contacts by correlating the paleo-composite electric log with the paleo and electric logs of wells where contacts have already been established. If there are no established contacts, or none that correlate by electric log, create a new contact on a distinctive shale horizon within the range of acceptable paleo picks on the paleo-composite electric log. (4) Correlate the contacts and other lithologic features on the paleo-composite electric log to all the other electric logs on the drillsite. (5) Where correlation is problematic, construct a cross section through the difficult area to help interpret the well data. (6) Once the wells are all correlated, a structure contour map can be constructed on any horizon, and the lithologic correlations may be added to cross sections.
ANALYSIS OF DIP DATA

In this study, dip data from oil companies were used in the construction of structure contour maps and cross sections. Some of the dip data are in the format of a tadpole plot, which is a computer-generated graph of well depth, dip direction, amount of dip, and quality (poor/weak, fair, good, or excellent). Tadpole plots generally have 10 - 30 data points (tadpoles) per 100 ft (30 m) well depth. Other individual dip correlations were made by geologists, generally with 1 - 2 picks per 100 ft (30 m). Some additional dip data are available from wells with core samples, but core dips give no information about dip direction.

Many wells have no dip data, and several wells have dip data that we were unable to obtain. In some wells, dip data are sparse for Quaternary and Pliocene intervals, because the stratigraphic target of the oil companies was generally lowest Pliocene or Miocene strata. Dip data may be unreliable where stratigraphic dips are nearly parallel to the well course. In this situation, a stratigraphic horizon on opposite sides of the well may be too far apart for the dipmeter to correlate, and the dipmeter will miscorrelate the strata. The resulting dip correlation is anomalous, and tends to be at a high angle to the well course. Examples of this phenomenon occur on cross section A-A' (Plate 2) in the upper Repetto of San Vicente SV-11 (~1500 ft - 3000 ft well depth), the middle Delmontian of SV-29 (~5800 - 7800 ft well depth), and near the lithologic base of the upper Mohnian of Laurel CH-2A (~4800 - 5800 ft well depth). Cross section B-B' (Plate 3) also has anomalous dips in the upper Delmontian of Seibu CH-1.

Dip data on tadpole plots were analyzed with the following procedure (in part from G. Huftile, pers. comm. 1991). (1) Scan the tadpole plot, looking for groups of consistent dip measurements. (2) Measure and record the most reliable dip datum, based on alignment of multiple tadpoles, every 50 or 100 ft (15 - 30 m) well depth, or less frequently where tadpoles are lacking in quality or quantity. (3) Assign each dip datum a quality of good, fair, or weak, based on the following criteria. A good dip datum, which is considered a reliable indicator of bedding dip, requires alignment of dip direction and dip amount (within 1-2°) of ≥3 tadpoles, within an interval of ≤100 ft (30 m). A fair dip datum, which is considered a probable indicator of bedding dip, requires alignment of dip direction and dip amount (within 3-10°) of ≥3 tadpoles, within an interval of ≤100 ft (30 m). A weak dip datum, which is considered a possible
indicator of bedding dip, requires alignment of dip direction and dip amount (within 1-2°) of 2 tadpoles, within an interval of ≤100 ft (30 m). (4) Plot good and fair dip data on cross sections. Weak dip data are used where there are no other dip data. Most of the good and fair dip data fit the surrounding dip data from the same well or a nearby well, or from constraints on a cross section.

Some wells have individual dip correlations by industry geologists. These individual correlations are generally in the form of a hand-written list, with each data point graded good, fair, or weak/poor. With only one or two data points per 100 ft (30 m) well depth, the rigorous method used to analyze tadpole plots was not feasible. An individual dip correlation was used on a cross section or structure contour map if the quality was good or fair, and if reliability was indicated by close agreement of two or more data points.
CROSS SECTIONS (PLATES 2 THROUGH 7)

Construction of cross sections

Construction of working cross sections is a crucial part of interpreting and presenting well data. In this study, eighteen working cross sections were constructed, with locations shown on Plate 1. All drillpads and all but three wildcat wells (UCH #14, La Tijera EH #1, Fairfax H.S. CH #1) are on the eighteen working cross sections. Six representative cross sections are presented in detail as Plates 2 (A-A') through Plate 7 (F-F'). Cross sections were constructed simultaneously with correlation of wells, to maximize our understanding of the structural and stratigraphic relationships.

Construction of working cross sections involved the following procedure (partly from G. Huftile, pers. comm., 1991). (1) Choose a line of section, at a high angle to strike, through a large number of wells. Where possible, choose wells with a maximum amount of paleo and dip data. Bends in the section are used to minimize projection along key wells. (2) Project well courses that fall within 500 ft (150 m) of the section. In several isolated areas having no wells within 500 ft (150 m), it was necessary to project wells more than 500 ft (150 m). Where dip data are available, well courses are projected along strike or down dip. At drillpads, where the data are very dense, wells requiring the smallest amount of projection are used, and/or those with the best data. (3) Add paleo control onto well courses on the cross section. (4) Add dip data onto well courses on the cross section. Each dip datum is shown as an apparent dip, projected onto the line of section. (5) Add lithologic correlations from electric logs onto well courses on the cross section. (6) Draw contacts that honor the paleo data, dip data, and lithologic correlations. Where dip data permit, folded contacts are drawn with kink bends. A kink bend is bisected by a fold hinge, except where the thickness of the bed is changing due to growth strata. (7) If there is a large area with no data, contacts may have to be added from structure contour maps, which have constraints away from the cross section.
Seismic reflection data

Seismic reflection lines were used to supplement well data on cross sections. Several proprietary vibroseis seismic reflection lines were obtained from Chevron U.S.A. Inc. and from Unocal Corporation. Good reflectors on the seismic lines tend to be confined to the gently dipping (≤ 25°) strata in the upper 1.5 - 2.0 seconds (two-way time) of the central trough and its flanks. This interval may include lower Quaternary strata, Pico strata, and/or upper Repetto strata. On the flanks of the central trough, beds of lower Repetto and older strata generally dip too steeply to be imaged as good reflectors.

Three seismic lines (2894-BY, 2894-AS, and LAB-80-1; locations shown on Fig. 3.2) have good reflectors in the Pliocene section. For each seismic line, the time section was converted to a depth section using velocities listed on the seismic line. The resulting depth section was projected onto a nearby cross section. Line 2894-BY has good south-dipping reflectors on the northern flank of the central trough that are shown on cross section A-A' (Plate 2). Line 2894-AS crosses the narrow central trough, and its reflectors are shown on cross section C-C' (Plate 4). Line LAB-80-1 has excellent reflectors across the widening central trough, south of cross section F-F' (Plate 7), where there are no wells within several thousand feet (~1000 m) of the line. Data from this seismic line alone are not sufficient to extend cross section F-F' to the south.
Figure 3.2. Location of three seismic reflection lines used in this study (2894-BY; 2894-AS; LAB-80-1). Seismic lines were converted to depth sections, and reflectors were plotted on cross sections A-A' and C-C' (Plates 2 and 4).
CONSTRUCTION OF STRUCTURE CONTOUR MAPS (FIG. 2.1; PLATE 8)

After correlating stratigraphic horizons on electric logs of wells, the data can be represented on structure contour maps. In this study, structure contour maps were constructed on the base of the Quaternary marine gravels (Qmg; Fig. 2.1) and at the Pico-Repetto contact (Plate 8). Other structure contour maps relevant to this study were constructed by Schneider (1994): the Repetto-Miocene contact (Plate 9), the Delmontian-Mohnian (Plate 10), the top of lower Mohnian Nodular Shale (Plate 11), and faults (Plate 12).

Construction of a structure contour map on a chosen horizon uses the following procedure. (1) Correlate wells, as outlined above. (2) Calculate the subsea depth of the horizon on each well, and plot it along the well course in map view. (3) Add dip data at the contact, where available. For the base Qmg and the Pico-Repetto contacts, which are locally unconformable, dips from the lowest part of the overlying beds are used, because they represent deformation since, and not before, the age of the contact. Dip data are taken as close as possible, and not more than 200 ft (60 m), from the contact. (4) Contour the subsea depths, honoring the depth values, the dip directions (which constrain the strike of contours), and the dip values (which constrain the spacing of the contour lines). (5) Areas that are difficult to contour are resolved by reanalyzing electric log correlations and cross sections. (6) For areas that are lacking in well data, the depth of the contact may be added to the structure contour map from cross sections, which are constrained by deeper and shallower data. (7) Work back and forth between cross sections and structure contour maps to resolve conflicts and infer the geometry of areas with little data.

The Pico-Repetto structure contour map (Plate 8) includes some data in the western and southern sections that are incorporated from other sources. These data are indicated by a circle-cross symbol. In the Baldwin Hills area, structure contours and the location of the Newport-Inglewood fault were compiled by H. Tsutsumi (1993; from an unpublished report by T.L. Wright; small versions of Wright’s maps appear in Wright, 1991). West of the northern extension of the Newport-Inglewood fault (Plate 8), data were analyzed by H. Tsutsumi (unpublished data, 1993).
CONSTRUCTION OF ISOPACH MAPS (PLATES 13 AND 14)

Isopach maps are used to help identify structural elements that were active during the time of deposition, based on the concept that strata thin over active anticlines and thicken in active synclines. Structure contour maps were constructed for the Pliocene Pico and Repetto stages (Plates 13 and 14; by this author), and for the upper Miocene Delmontian and Mohnian stages (Plates 15 and 16; Schneider, 1994). An isopach map of the Quaternary strata was not constructed, because it is essentially the same as the structure contour map on the base of the Quaternary strata.

Isopach maps of the Pliocene units were constructed using the following method. (1) Thicknesses were measured along ten cross sections with detailed Pliocene data, including A-A' through F-F' (Plates 2 through 7; cross section locations shown on Plates 1, 13, and 14). Where sections cross, the one with better data, or the one crossing strike closer to orthogonal, was used. The ten cross sections include data from all eight drillpads and all but five wildcat wells, which are indicated as isolated data points on the isopach maps. Along the cross sections, thickness was measured every 1000 ft (305 m), with supplemental measurements at 500-foot (150-meter) intervals. Measurement was made perpendicular to the upper contact of the unit. Pico and Repetto strata both thicken dramatically in places (shown schematically in Fig. 3.3) due to syndepositional growth of structures. Taking one measurement perpendicular to the top contact (Fig. 3.3a) could result in a significant overestimate of the thickness in an area with growth strata. The method used here (Fig. 3.3b) was to measure each of the upper, middle, and lower members of Pico and Repetto strata separately, perpendicular to the top contact of each member. The three measurements (U + M + L) were added together for a total Pico measurement, or total Repetto measurement.

(2) A thickness measured on a cross section is an apparent thickness, because the cross sections are not exactly parallel to dip direction. A correction was applied, where necessary, to arrive at a true thickness. Apparent thickness is nearly equal to true thickness (within 5%) where the top-contact dip is less than 20°, or where the cross section direction is within 20° of dip direction. No correction was applied where true thickness was within 5% of apparent thickness, including the vast majority of the ~325 Pico and Repetto measurements. Eight Repetto apparent-thickness measurements, with steep dips and/or with cross section oblique to dip direction, required an adjustment of
Figure 3.3. Two methods of measuring thickness of growth strata on a cross section. (a) One measurement, taken perpendicular to the top contact, overestimates the thickness of the unit. (b) The method used in this study involves measuring upper, middle, and lower thicknesses separately, resulting in a more accurate estimate of thickness.

5-13%. No apparent thickness measurement required a correction of more than 13%, primarily because most cross sections are nearly parallel to dip direction.

(3) The thicknesses were contoured. Individual contour lines were carried across the wavy unconformity line (Plates 13 and 14), which marks the southern limit of post-depositional (erosional) thinning of the Pico and Repetto. This unconformity is shown in cross section view on Plates 2 through 7. Pico and Repetto strata also show northward syndepositional thinning (Plates 2 through 7) in the same area. Prior to erosion, Pico and Repetto strata probably thinned to zero not far north of the contoured erosional zero-thickness line. In the Hollywood basin, there were not enough data points to contour.
CHAPTER 4: PLIOCENE STRATIGRAPHY AND STRUCTURES

INTRODUCTION

The Pliocene structural evolution of the northern Los Angeles basin can be interpreted from the stratigraphic record, mapped in the subsurface from an extensive dataset of oil wells. The thickness and lithology of Pliocene strata reflect the influence of folds and faults that were active during deposition. The structural geometry we see today results from both syn- and post-depositional deformation.

Cross sections A-A’ through F-F’ (Plates 2 through 7; locations on Plate 1) depict the thickness and structure of the Pliocene strata. Sandstone bodies are also shown, because the coarseness of strata was influenced by structurally-controlled sea-floor topography. Coarser-grained sediments were deposited by turbidity currents in topographically low areas (active synclines), and finer-grained hemipelagic sediments were deposited over topographically higher areas (active anticlines).

Structure contour maps show the net deformation since deposition of the stratigraphic horizon that is contoured. The structure contour map on the base of the Quaternary marine gravels (Fig. 2.1) shows Quaternary deformation. The structure contour map of the Pico - Repetto contact (Plate 8), which represents deformation during the upper Pliocene and Quaternary, bears a strong resemblance to the Pico isopach map (Plate 13), which represents deformation during Pico deposition (late Pliocene to early Pleistocene). The structure contour map of the Repetto - Delmontian contact (Plate 9) represents all Quaternary and Pliocene deformation.

An isopach map of Pico strata (Plate 13) shows the thickness of strata deposited during the late Pliocene and early Pleistocene, while the isopach map of Repetto strata (Plate 14) shows the thickness of strata deposited during the early Pliocene. The thickness and distribution of these strata result from the location and activity of structures present during deposition. A constant supply of sediments allowed the structural topography to be filled in, with thicker deposits in synclines and thinner deposits over anticlines.

In this chapter, the stratigraphy and location/timing of structures of each area are presented together, and the areas are described from west to east. The East Beverly Hills area is presented first, including cross section A-A’ (Plate 2 - Saturn CH), and
cross section B-B' (Plate 3 - Packard drillsite). The next region covered is the transition between the East Beverly Hills and the Las Cienegas areas, shown on cross section C-C' (Plate 4 - St. Elmo CH). The third region covered is the Las Cienegas area, including cross section D-D' (Plate 5 - PE drillsite), cross section E-E' (Plate 6 - 4th Ave. drillsite), and cross section F-F' (Plate 7 - Murphy drillsite). The final area presented is the Hollywood basin, located at the north of the study area, on cross sections A-A', D-D', and F-F' (Plates 2, 5, and 7).

References to specific wells will use the following abbreviations: CH for Core Hole; EH for Exploratory Hole; OH for original hole; R/D-1 for Redrill #1; drillsite for a town-lot surface location from which 10 to 100 wells were drilled. Names of wells and drillsites are given on Plate 1, which shows the location of cross sections constructed in this study.
The Pico strata (late Pliocene to early Pleistocene) in the East Beverly Hills area are a lithologically uniform sequence of fine-grained marine sedimentary rocks that thicken south into the central trough. The Pico strata are primarily claystone with secondary interbedded siltstone and occasional shale. According to mud logs, interbedded sandstones are uncommon to absent in these fine-grained rocks, except in the uppermost upper Pico and in the central trough (entire Pico section). The uppermost upper Pico strata are a coarsening-upward sequence, which is expressed as a funnel shape on electric logs (Fig. 4.1). The uppermost Pico is transitional between the fine-grained, deeper-marine Pico strata and the coarse-grained, shallow-marine Quaternary strata (Chapter 2). The claystone/siltstone lithology is present throughout the remainder of the Pico section, and continues down into the upper Repetto (Fig. 4.1). For the majority of the Pico, there is a rhythmic alteration between claystone and siltstone, with siltstone dominant every 20 - 50 ft (6 - 15 m), as seen on a representative electric log from the Packard drillsite (Fig. 4.1). This electric-log pattern, as well as many specific features, can be correlated in wells from the East Beverly Hills area (Packard and West Pico drillites; Saturn CH) and wells west of the Newport-Inglewood fault (Rancho, Hillcrest, and Community drillites; R, H, and C on Fig. 4.2).

In the East Beverly Hills area, the early Pliocene Repetto strata are quite distinct from the Pico strata. The middle and lower Repetto strata are dominated by sandstone packages up to ~100 ft (~30 m) thick (Fig. 4.1). According to the mud logs of wells in the East Beverly Hills area, the sandstone packages are generally 40 - 80% sandstone, interbedded with claystone and siltstone. The fine-grained strata between the major sandstone bodies generally include at least 10% interbedded sandstones. Some Repetto sandstones can be correlated between drillites, but others vary considerably from one drillsite to another, necessitating the use of paleo for correlation.

Variations in thickness and lithology of the Pico and Repetto strata yield clues to the structural history of the East Beverly Hills area. The most basic observation is that Pico lithology is fairly uniform (over time and distance), suggesting a relatively uniform structural and depositional setting. Repetto lithology, however, varies considerably (over time and distance), suggesting that the environment of deposition
Figure 4.2. Location of cross sections used in Chapter 4. Cross sections A-A' through F-F are Plates 2 through 7. Cross section I-I' is Figure 4.4; cross section J-J' is Figure 4.5; cross section K-K' is Figure 4.8. Fault scarps (from Dolan and Sieh, 1992) are: MPF = MacArthur Park fault; SMF = Santa Monica fault; WBHL = West Beverly Hills lineament. NIF = Newport-Inglewood fault. Location of Metro Rail boreholes (CEG 15-23) are shown by the numbers 15 through 23. Abbreviations for drillsites and selected wildcat wells are: A = Adamson CH; C = Community drillsite; DPR = Dep't. Parks and Rec. CH; D = Dublin CH; Gen = Genesee EH; JB = Jade Buttram drillsite; H = Hillcrest drillsite; M = Murphy drillsite; P = Packard drillsite; PE = Las Cienegas PE drillsite; PT = Pacific Telephone CH; R = Rancho drillsite; S = Saturn CH; SE = St. Elmo CH; SV = San Vicente drillsite; WB = Washington Blvd. EH; WP = West Pico drillsite; 4A = 4th Avenue drillsite.
was affected by active structures. Variations in thickness of the Pico and Repetto can be seen on cross sections A-A' and B-B' (Plates 2 and 3), and on isopach maps of the Pico and Repetto (Plates 13 and 14). Variations in lithology of the Pico and Repetto can be seen on cross sections A-A' and B-B' (Plates 2 and 3), which show Pliocene sandstones from electric logs and mud logs.

**Timing of Pico structures, based on thickness and lithology**

The isopach map of Pico strata (Plate 13) shows thickening southward in the East Beverly Hills area from 0 ft (0 m) near the San Vicente drillsite to ~5000 ft (~1525 m) in the central trough. This suggests that thickness and grain size of Pico strata were largely controlled by relative subsidence between the structurally high area to the north and the central trough to the south. On cross section B-B' (Plate 3), this southward thickening has the overall form of a south-dipping monocline, with the monoclinic high to the north, complicated by the secondary South Salt Lake anticline. On cross section A-A' (Plate 2), the monocline has plunged several thousand feet deeper, allowing Pliocene strata to onlap the monoclinic high at the San Vicente drillsite. During deposition of the Pico strata, the central trough was an active syncline, subsiding relative to the region to the north. The position of Pico and upper Repetto contacts in the central trough of cross section A-A' (Plate 2) was constrained by a depth section of selected reflectors from seismic reflection line 2894-BY (Fig. 4.3). Relative subsidence of the central trough resulted in some topographic relief, which caused minor ponding of sand during Pico deposition. Mud logs from Adamson CH (cross section A-A', Plate 2) and Genesee EH (cross section B-B', Plate 3) indicate that the Pico strata in the central trough have more interbedded sandstones than the Pico strata to the north (e.g., Saturn CH and Packard drillsite). Sandstone interbeds in the central trough make up 10-20% of the entire Pico section, reaching 30 - 60% in the lowermost Pico. This contrasts with the typical Pico strata from the slope of the monocline (Fig. 4.1), which include 0%, and locally 10% sandstone interbeds. Despite the increased incidence of sandstone interbeds in the central trough, the rhythmic variation in grain size typical of the Pico (Fig. 4.1) is present, although somewhat coarser-grained and wider-spaced, in the Adamson and Genesee electric logs.

The southward-thickening trend is interrupted by the East Beverly Hills anticline and syncline, across which Pico strata remain at a nearly constant thickness of
Figure 4.3. Seismic line 2894-BY in the East Beverly Hills area. Location of seismic line is shown on Figure 3.2. Two-way time is shown in seconds. The southern end of the line (left) shows reflectors dipping into the central trough. The northern end (right) is at the approximate location of the East Beverly Hills anticline. The original seismic line goes to a depth of 3.8 seconds two-way time, but strata below ~2.0 seconds are dipping too steeply to be imaged by seismic reflection methods. (a) Without interpretation.
Figure 4.3 (continued). (b) With interpretation. Reflectors drawn here were converted to a depth section, and are plotted on cross section A-A' (Plate 2).
2000 - 2500 ft (610 - 760 m), forming a flat bench in the Pico isopachs (Plate 13). This structural bench can also be seen on the structure contour map of the Pico - Repetto contact (Plate 8), and on cross sections A-A' (Plate 2, Saturn CH) and B-B' (Plate 3, Packard drillsite). Wright (1991) noted that the East Beverly Hills fold was relatively inactive during Pico deposition, which is supported by the presence of a flat bench rather than an actual anticline/syncline pair. The lithologic uniformity of the Pico strata in the East Beverly Hills area also indicates that this area had little topographic relief during Pico deposition. In wells drilled west from the West Pico drillsite, a localized decrease in grain size over the East Beverly Hills anticline occurs in the lowermost Pico, indicating that the anticline had minor topographic relief at the beginning of Pico deposition. This West Pico location (cross section I-I', Fig. 4.4; location on Fig. 4.2) is one of two places where the Pico - Repetto contact is actually a small anticline, rather than just a bench. The other site is just southeast of the Packard drillsite (Plate 8), where the Pico - Repetto contact has been warped locally into a small anticline. There is no evidence of syndepositional topographic relief on this minor anticline, which probably formed after deposition of the lowermost Pico. The East Beverly Hills fold was minimally active during deposition of most of the Pico, as evidenced by the slight upward inflection of the upper/middle and middle/lower Pico contacts. This slight upward warp formed the structural bench, but not an anticline in most places. The East Beverly Hills fold was therefore active (but at a very subdued pace) at least into the upper Pico (early Pleistocene). If the fold affected the base of the Quaternary marine gravels, the upward inflection would be smaller than the errors in our data, and would be difficult to recognize.

At the Pico - Repetto contact (Plate 8), the East Beverly Hills bench occurs at a depth of ~3000 ft (~900 m) at the West Pico drillsite, and ~2000 ft (~600 m) at the Packard drillsite, indicating that Pico strata are ~1000 ft (~300 m) thicker at the west end of the bench than at the east end. This 1000-foot thickness change can also be seen on the Pico isopach map (Plate 13), which shows a thickness of ~2500 ft (~760 m) at the West Pico drillsite and ~1500 ft (~460 m) at the Packard drillsite. Therefore, the western end of the East Beverly Hills bench was subsiding relative to the eastern end, during Pico deposition. Another change along the East Beverly Hills bench is that the western end is very broad, while the eastern end is a tighter fold, with a shorter wavelength, larger amplitude, and steeper limbs. This eastward tightening of the East Beverly Hills anticline can be seen in a comparison of cross sections A-A' and B-B' (Plates 2 and 3), on the structure contour map of the Pico - Repetto contact (Plate 8),
Figure 4.4. Cross section I-I' through the West Pico drillsite, East Beverly Hills area. Location shown on Figure 4.2. No vertical exaggeration. Growth of East Beverly Hills anticline (EBHA) occurred primarily during deposition of Delmontian strata (thinned over anticline), lower Repetto strata (not deposited on crest of anticline), and middle Repetto strata (sandstones pinch out over anticline). Stippled areas represent sandstones; open circles indicate paleo control; squares represent the bentonite at the Delmontian - Mohnian contact.
and on the Pico isopach map (Plate 13). The eastward tightening of the East Beverly Hills anticline and syncline is related to the position of the monoclinal high to the north. In the eastern East Beverly Hills area (cross section B-B', Plate 3), late Pliocene relative uplift on the monoclinal high and South Salt Lake anticline produced a structural buttress that impinged on the position of the East Beverly Hills anticline. The presence of the monocline created a space problem, causing the East Beverly Hills anticline to be squeezed tighter, and uplifted relative to its position to the west. The monoclinal high and South Salt Lake anticline plunge and die to the west, under the San Vicente drillsite (north end of cross section A-A', Plate 2), allowing deposition of Pliocene strata farther north, over the edge of the deep monocline. The plunging and dying monocline impinged less on the position of the East Beverly Hills anticline, which is wider and lower here.

Pico strata thin to the north of the East Beverly Hills anticline and syncline, indicating significant syndepositional growth on the broad monoclinal uplift. The fanning dips in the thinned Pico section of Union CH-11 (cross section B-B', Plate 3) and Tower CH (Fig. 4.5; located between A-A' and B-B') indicate that growth of the monocline caused progressive uplift and south tilting during Pico deposition. The electric-log pattern of interbedded claystone with siltstone is present in Union CH-11 and Tower CH. Because the electric logs are difficult to correlate with the typical Pico electric log (Fig. 4.1), contacts are partly based on paleo samples.

It is not possible to determine where the Pico strata originally thinned to zero at the late Pliocene northern basin margin, because the evidence has been removed by latest Pico and post-Pico erosion. North of the San Vicente drillsite (cross section A-A', Plate 2) and Seibu CH (cross section B-B', Plate 3), the Quaternary marine gravels rest unconformably on successively older Pico strata. The southernmost extent of this unconformity is shown on the Pico isopach map (Plate 13) by the wavy line. North of the San Vicente drillsite on cross section A-A' (Plate 2), the Pico strata were eroded on the monoclinal high in latest Pico time. Subsequent initiation of and slip on the Wilshire fault (Chapter 2) allowed the Hollywood basin to form, and the late Pico unconformity was buried under Quaternary marine gravels.
Figure 4.5. Cross section J-J' through Saturn CH and Tower CH, East Beverly Hills area. Distribution of sandstones, shown on electric logs, demonstrate that the East Beverly Hills anticline and syncline were most active during Repetto deposition. Reverse slip on the San Vicente fault caused middle Repetto uplift, which resulted in an angular unconformity (wavy line). Cross section location (between A-A' and B-B') is shown on Figure 4.2.
Timing of Repetto structures, based on thickness and lithology

The isopach map of Repetto strata (Plate 14) shows thickening southward in the East Beverly Hills area, from 0 ft (0 m) at the San Vicente drillsite, to ~4500 ft (~1370 m) in the central trough. This southward thickening resulted from subsidence of the central trough relative to the Pliocene monocinal uplift to the north. The westward plunge of the monocline, discussed above, allowed Repetto strata to be deposited farther north at San Vicente drillsite (cross section A-A', Plate 2) than at the Jade Buttram drillsite (cross section B-B', Plate 3). Relative subsidence of the central trough resulted in a topographically lower area, which allowed ponding of Repetto turbidite sands. Mud logs from Adamson CH (cross section A-A', Plate 2) and Genesee EH (cross section B-B', Plate 3) indicate that the Repetto sandstone packages thicken and coarsen into the central trough, as seen on cross sections A-A' and B-B' (Plates 2 and 3). According to mud logs, the number of Repetto sandstone interbeds in the central trough is highly variable, averaging ~40% and reaching nearly 100% in some sandstone packages. This contrasts with the typical Repetto strata from the Saturn CH or Packard area, where the sandstone interbeds are ~20% of the strata, with a maximum of 80% in some sandstone packages.

The southward-thickening trend of the Repetto strata is interrupted by the East Beverly Hills anticline and syncline, which can be seen on cross sections A-A' and B-B' (Plates 2 and 3), on the Repetto - Delmontian structure contour map (Plate 9), and on the Repetto isopach map (Plate 14). The Repetto isopach map (Plate 14) shows that ~2500 ft (~760 m) of Repetto strata fill the East Beverly Hills syncline, while less than 1500 ft (460 m) of Repetto strata are present over the East Beverly Hills anticline. Therefore, ~1000 ft (~300 m) of relative subsidence occurred between the East Beverly Hills syncline and anticline during Repetto deposition, which is minor compared to the ~4500 ft (~1370 m) relative subsidence associated with the monoclinal uplift. An increase of interbedded sandstones in the East Beverly Hills syncline (cross sections A-A', J-J', B-B'; Plate 2, Fig. 4.5, Plate 3) indicates that this fold was active during Repetto deposition, producing topographic relief that allowed for ponding of sands in the synclinal trough. On Figure 4.5, the thickness and location of sandstones are demonstrated by electric logs, which show that the Repetto strata in the East Beverly Hills syncline (Saturn CH, R/D-2, projected from along strike; Tower CH, OH) have more sandstone than the Repetto strata over the East Beverly Hills anticline (Saturn CH, OH and R/D-1).
At the west end of the East Beverly Hills anticline (West Pico drillsite), the lower Repetto strata thin to zero over the top of the East Beverly Hills anticline (Fig. 4.4; Plate 13), indicating significant local topographic relief during deposition of the lower Repetto. Apparently, the western part of the East Beverly Hills anticline (West Pico drillsite, Fig. 4.4) had greater topographic relief than the eastern part (Packard drillsite, cross section A-A', Plate 2) during lower Repetto deposition, but the actual amount of relief cannot be determined. The topographic relief of the East Beverly Hills anticline was more subdued, but still present, during middle Repetto deposition, as evidenced by the thinner, finer-grained strata on the anticline, compared to the thicker, sandier section in the syncline to the north and the central trough to the south. Cross sections I-I' and A-A' (Fig. 4.4; Plate 2) show that the growth of the East Beverly Hills anticline was greatest during lower and middle Repetto deposition, but decreased in the upper Repetto, which shows relatively little thickness change or lithologic change over the fold. Wright (1991) also noted that lower and middle Repetto sandstones pinch out over the East Beverly Hills anticline. On cross section B-B', thickness changes over the East Beverly Hills fold indicate that fold growth was fairly constant during deposition of the lower, middle and upper Repetto, but the upper Repetto shows little lithologic variation over the fold. Growth of the East Beverly Hills fold decreased in the middle of the upper Repetto, which is reflected in the lithologic change from sandy, variable lithology (typical of the Repetto) to the rhythmic claystone/siltstone pattern (typical of the overlying Pico; see stratigraphy section, above).

On the Repetto isopach map (Plate 14), Repetto strata are ~1500 ft (~460 m) thick along most of the East Beverly Hills anticlinal crest, and ~2500 ft (~760 m) thick along most of the synclinal trough. Therefore, unlike during the Pico, roughly equal subsidence occurred along East Beverly Hills anticline (~1500 ft; ~460 m) and along the syncline (~2500 ft; ~760 m) during Repetto deposition. The eastward tightening of the East Beverly Hills fold, discussed above for the Pico strata, was also present during Repetto deposition. This eastward tightening of the fold can be seen in a comparison of cross sections A-A' and B-B' (Plates 2 and 3), on the structure contour map of the Repetto - Delmontian contact (Plate 9), and on the Repetto isopach map (Plate 14). This tightening of the East Beverly Hills fold is related to the position of the monoclinal high to the north, which continued to influence Pico deposition also. In the eastern East Beverly Hills area (cross section B-B', Plate 3), early Pliocene relative uplift on the monoclinal high and South Salt Lake anticline produced a structural buttress that impinged on the position of the East Beverly Hills fold. This space
problem caused the East Beverly Hills fold to be squeezed tighter than it was to the west. The monoclinal high and South Salt Lake anticline plunge and die to the west, under the San Vicente drillsite (north end of cross section A-A', Plate 2), allowing deposition of Pliocene strata farther north, over the end of the west-plunging, dying monocline. The monocline impinged less on the position of the East Beverly Hills anticline, which is wider here.

Repetto strata thin to the north of the East Beverly Hills syncline, indicating significant syndepositional growth on the broad monoclinal uplift. Growth of the monoclinal uplift, however, varied along strike in the east Beverly Hills area. On cross section A-A', the monoclinal high was growing during deposition of lower Repetto strata, which onlap and pinch out onto the north side of the East Beverly Hills syncline. With no monoclinal uplift, there would have been no East Beverly Hills syncline - just a broad low area north of the East Beverly Hills anticline. The San Vicente fault, which offsets Delmontian strata under the East Beverly Hills syncline, was not active at any time during Repetto or Pico deposition. At the San Vicente drillsite, the lower Repetto strata thin to zero, allowing thinned middle and upper Repetto strata to rest unconformably on Mohnian strata. This indicates that slower growth of the monocline continued during middle and upper Repetto deposition. The middle and upper Repetto strata originally thinned to zero north of the San Vicente drillsite, but evidence of this northern basin margin has been removed by post-Pico erosion. The southernmost extent of this unconformity, where Quaternary marine gravels rest directly on Repetto strata, is shown on the Repetto isopach map (Plate 14) by the wavy line.

On cross sections B-B' (Plate 3) and J-J' (Tower CH, Fig. 4.5), uplift of the monocline during lower Repetto deposition occurred north of the present-day location of the East Beverly Hills syncline. Lower Repetto strata of the Packard drillsite and Tower CH have relatively constant thickness and lithology north of the East Beverly Hills anticline, indicating that there was no East Beverly Hills syncline present at this location. The north side of the syncline, which was formed by the monoclinal uplift, was located north of the lower Repetto strata that are near Tower CH (J-J', Fig. 4.5) and Packard wells P-60 and P-69 (B-B', Plate 3). Evidence for the north side of the lower Repetto syncline, and therefore the monoclinal uplift, was subsequently eroded. In the middle Repetto, the northern limb of the East Beverly Hills syncline moved south as the edge of the monocline stepped south, due to reverse slip on the San Vicente fault (cross section B-B', Plate 3). In the middle of middle Repetto deposition, an episode of reverse slip on the San Vicente fault caused uplift and erosion of the lower Repetto
strata in the hangingwall of this fault, in the vicinity of Tower CH R/D-2 (cross section J-J', Fig. 4.5) and Seibu CH (cross section B-B', Plate 3). Middle Repetto deposition continued uninterrupted in the East Beverly Hills anticline and syncline, but the thickness and grain size of middle Repetto strata decrease on the north limb of the syncline (cross sections J-J' and B-B'; Plate 3 and Fig. 4.5). Near Tower CH R/D-2 (cross section J-J', Fig. 4.5) and Seibu CH (cross section B-B', Plate 3), a thin package of middle and upper Repetto strata overlaps the mid-middle Repetto unconformity, as growth of the monocline continued and slip on the San Vicente fault slowed or stopped. Just north of Tower CH R/D-2 (cross section J-J', Fig. 4.5) and Seibu CH (cross section B-B', Plate 3), the upper-middle and upper Repetto strata are shown onlapping onto the middle Repetto unconformity, thinning to zero near the Metro Rail boring CEG 19 (cross section B-B', Plate 3). The position of the Pliocene - Delmontian contact is constrained in CEG-19, which has two samples with diatoms in the b subzone of the Nitzschia reinholdii zone, equivalent to the mid-Delmontian (J. Barron, pers. comm., 1993). CEG-19 also has steeper dips (mostly 40 - 50°) that corroborate the Delmontian fold shape, which is inferred on B-B' from constraints along strike. A dip of 20°, located above the diatom samples and below the Quaternary marine gravels, probably occurs in Pliocene strata, but there are no paleo data to indicate whether these are Repetto (as shown) or Pico strata.

**Timing of Delmontian structures, based on thickness and lithology**

Many of the patterns discussed for the Repetto strata in the East Beverly Hills area began during late Delmontian deposition, in the latest Miocene. Upper Delmontian sandstones are localized in the East Beverly Hills syncline, and thin to the north and south (cross sections A-A' and B-B', Plates 2 and 3). The isopach map of the Delmontian strata (Plate 15) shows some thickening in the East Beverly Hills syncline and thinning over the anticline. Wright (1991) also noted that Delmontian sandstones pinch out over the East Beverly Hills anticline. The initiation of the East Beverly Hills fold was therefore in the middle to late Delmontian. The isopach map of the Delmontian strata (Plate 15) does not show any systematic thickening to the south, indicating that growth of the monoclinal uplift began in latest Delmontian or earliest Repetto time.
Summary of East Beverly Hills area Pliocene structural evolution

The dominant Pliocene structure in the East Beverly Hills area is the monoclinal uplift, which affected both Pico and Repetto deposition. The monocline originated during latest Delmontian or earliest Repetto deposition. The westward plunge of the monocline at the San Vicente drillsite was present throughout the Pliocene, and it can be seen on structure contour maps of the Pico - Repetto and Repetto - Delmontian contacts (Plates 8 and 9), and on the Pico and Repetto isopach maps (Plates 13 and 14).

We (Hummon, Schneider, Yeats) propose that the monoclinal uplift was caused by a basement reverse fault, located far below well control, referred to here as the Monocline fault. Reverse slip on the Monocline fault would cause relative subsidence (increased vertical distance) and shortening (decreased horizontal distance) between the footwall and the hanging wall. Therefore, Pliocene sediments deposited in the central trough would also undergo subsidence and convergence relative to sediments on the monoclinal high to the north. We propose that the proportions of relative subsidence and shortening measured in the Pliocene growth strata reflect the dip of the underlying Monocline fault. Relative subsidence can be estimated by comparing sediment thickness in the central trough with sediment thickness on the monoclinal high. The difference between the thicknesses is caused by relative subsidence. The amount of shortening can be estimated by measuring bed lengths at the top and bottom of a stratigraphic interval. The fault dip (D) is determined from the subsidence (V) and shortening (H), using: \( \tan(D) = H/V \). Schneider (1994) carried out these calculations, and presents a discussion of the assumption and methods, which were developed by Schneider, Hummon, and Yeats. The calculations indicate that the Monocline fault dips north between 55° and 61°, depending on the assumptions used.

Near the surface, most of the slip associated with the Monocline fault has been distributed into the monoclinal fold. Some of the slip on the deep fault, however, is transmitted to the near-surface on the San Vicente fault, whose dip is very close to that of the deeper fault. The near-surface slip on the San Vicente fault caused the localized Salt Lake anticline to form as a secondary feature on the primary monoclinal uplift.

The existence of a monocline in the hanging wall of the fault suggests that the fault geometry may be planar. The alternative, a ramp-flat fault geometry (Suppe, 1983; Suppe and Medwedeff, 1990), would cause an anticline with a backlimb to form in the hanging wall, above the bend in the fault. The data do not show a backlimb on the monocline. The geometry of a straight fault continuing down below the
seismogenic zone has recently been suggested for reverse faults in the Ventura basin (Yeats, 1993), based in part on geodetic evidence for convergence rates (Donnellan et al., 1993).

The East Beverly Hills fold was a secondary feature to the monocline during the entire Pliocene, and it was more active during Repetto than Pico deposition. Oil wells do not penetrate any significant reverse fault that could cause the East Beverly Hills fold. We believe that the East Beverly Hills fold may be a rabbit-ear fold (Brown, 1988), a geometry that alleviates volumetric crowding caused by parallel folding. Bedding slip allows a secondary fold, verging in the opposite direction to the primary fold, to form on the steep limb of an asymmetric fold (Brown, 1988). In the case of the East Beverly Hills area (cross section B-B'), the main fold is the south-vergent monocline, with the secondary north-vergent East Beverly Hills located on the steep limb of the monocline. The eastward tightening of the East Beverly Hills rabbit-ear fold is caused by an eastward increase in volumetric crowding by the monoclinal high.
ST. ELMO AREA, BETWEEN EAST BEVERLY HILLS
AND LAS CIENEGAS AREAS

Stratigraphy

The Pico strata (late Pliocene to early Pleistocene) in the transitional area between the East Beverly Hills and Las Cienegas areas (cross section C-C', Plate 4) are similar to those in the East Beverly Hills area. The interbedded claystone with siltstone has the characteristic electric-log pattern seen in the East Beverly Hills area (Fig. 4.1). The small-scale features of the lower Pico strata in St. Elmo CH (cross section C-C', Plate 4) can easily be correlated with the lower Pico in the East Beverly Hills area by electric log. The middle and upper Pico have the characteristic electric-log pattern and lithology of the East Beverly Hills area (Fig. 4.1), including the coarsening-upwards sequence in the uppermost Pico, but the small-scale features cannot be correlated between the two areas. The Pico strata thicken into the central trough to the south, and thin onto the monoclinal high to the north.

In the transitional area between the East Beverly Hills and Las Cienegas areas, the early Pliocene Repetto strata are coarser grained than the overlying Pico strata. The uppermost Repetto strata have the interbedded claystone with siltstone lithology that characterizes the Pico strata, which was also true in the East Beverly Hills area. The upper-middle Repetto and the lower Repetto strata have sandstone packages up to ~100 ft (~30 m) thick, with sandstones comprising ~40 - 80% of the strata, according to mud logs in St. Elmo CH. The finer-grained strata generally include 0 - 10% interbedded sandstones. The major sandstone-dominated and finer-grained intervals of the lower Repetto can be correlated between St. Elmo CH and the East Beverly Hills area.

Timing of Pico structures, based on thickness and lithology

The isopach map of Pico strata (Plate 13) shows thickening southward in the transitional St. Elmo area from 0 ft (0 m) at Highland CH-2 to ~6000 ft (~1830 m) in the central trough. Deposition of Pico strata was largely controlled by relative subsidence between the monoclinal uplift to the north and the central trough to the south (cross section C-C', Plate 4). The position of the Pico contacts in the central
trough of cross section C-C' (Plate 4) was constrained by a depth section of selected reflectors from seismic reflection line 2894-AS (Fig. 4.6). The isopach map of Pico strata (Plate 13) and the structure contour map of the Pico - Repetto contact (Plate 8) are similar to the east end of the East Beverly Hills area, but without the extra complication of the structural bench associated with the East Beverly Hills anticline. Relative subsidence of the central trough caused some topographic relief, which resulted in deposition of coarser strata than to the north. Mud logs from Dep't. Parks and Rec. CH (cross section C-C', Plate 4) indicate that the upper and upper-middle Pico strata in the central trough are coarser-grained than the Pico strata to the north (e.g. St. Elmo CH), with more siltstone throughout, and with several sandstone bodies (sandstone beds comprise 20 - 90%). This contrasts with the typical Pico strata from the slope of the monocline, which have few sandstone and siltstone interbeds. The lower-middle and lower Pico strata are much coarser-grained than the Pico strata to the north (St. Elmo CH), with the amount of siltstone approaching the amount of claystone present. The lower-middle and lower Pico strata in Dep't. Parks and Rec. CH include ≥20% sandstone interbeds throughout the section, with an average of ~40% sandstone and a maximum of 90% sandstone. Despite the increased sandstone content, the rhythmic variation in grain size typical of the Pico (Fig. 4.1) is present, although much coarser-grained and wider-spaced, in the Dep't. Parks and Rec. CH electric log.

The central trough Pico strata at cross section C-C' are coarser-grained and thicker than the central trough Pico strata at cross sections A-A' and B-B'. Just west of cross sections A-A' and B-B' (Plates 2 and 3) is the northwestern end of the Quaternary and Pliocene central trough. The Pico strata of the central trough show clear evidence of a deeper basin at the position of cross section C-C' than B-B'. The Pico strata in Dep't. Parks and Rec. CH (cross section C-C', Plate 4) have more siltstone and sandstone interbeds than at Genesee EH (cross section B-B', Plate 3). The lower-lower Pico strata in Dep't. Parks and Rec. CH include 40 - 90% sandstone interbeds, while Genesee EH has only 30 - 60% sandstone interbeds.

Pico strata thin to the north of St. Elmo CH on cross section C-C' (Plate 4), indicating significant syndepositional growth on the monoclinal uplift. Paleo samples from Union CH-20 (cross section C-C', Plate 4) indicate that a complete section of upper, middle, and lower Pico is present, but very thin (total ~200 ft; ~60 m). Pico strata must have originally thinned to zero just north of Union CH-20, where post-Pico erosion has removed the very thin Pico strata (cross section C-C', Plate 4), allowing the Quaternary marine gravels rest unconformably on successively older Pico strata. The
Figure 4.6. Seismic line 2894-AS across the central trough, near St. Elmo CH. Location of seismic line is shown on Figure 3.2. Two-way time is shown in seconds. The original seismic line goes to a depth of 5.0 seconds two-way time, but strata below ~1.0 second are not imaged well on this seismic line, due to signal attenuation and steep dips.

(a) Without interpretation.
Figure 4.6 (continued). (b) With interpretation. Reflectors drawn here were converted to a depth section, and are plotted on cross section C-C' (Plate 4).
Pico and Repetto strata are completely eroded at the location of Metro Rail boring CEG-18, which has diatoms indicating a latest Miocene (Delmontian) age (J. Barron, pers. comm., 1993), and ashes from the latest Miocene (Sarna-Wojcicki, pers. comm. 1993). The southernmost extent of the post-Pico unconformity is shown on the Pico isopach map (Plate 13) by the wavy line. This unconformity was caused by Quaternary uplift of the Wilshire arch (Chapter 2).

**Timing of Repetto structures, based on thickness and lithology**

The isopach map of Repetto strata (Plate 14) shows thickening southward in the East Beverly Hills area from 0 ft (0 m) at Highland CH-2 to ~4500 ft (~1370 m) in the central trough. This southward thickening resulted from subsidence of the central trough relative to the Pliocene monoclinal uplift to the north. Relative subsidence of the central trough resulted in topographic relief, which allowed ponding of Repetto turbidite sands. Mud logs from Dep't. Parks and Rec. CH (cross section C-C', Plate 4) indicate that the upper Repetto sandstone packages thicken and coarsen into the central trough. The upper Repetto sandstone interbeds make up 10 - 70% of the strata, averaging ~50%. This contrasts with the upper Repetto strata of St. Elmo CH, where sandstones in the upper Repetto strata make up 0 to 60%, and average ~20% of the strata.

The upper Repetto strata in the central trough at cross section C-C' are coarser-grained and thicker than at cross sections A-A' and B-B'. Just west of cross sections A-A' and B-B' (Plates 2 and 3) is the northwestern end of the Quaternary and Pliocene central trough. The upper Repetto strata of the central trough show clear evidence of a deeper basin at the position of cross section C-C' than B-B'. The upper Repetto strata in Dep't. Parks and Rec. CH (cross section C-C', Plate 4) have more interbedded sandstones (10 - 70%, averaging ~50%) than at Genesee EH (10 - 60%, averaging ~30%; cross section B-B', Plate 3). There are no data on the middle and lower Repetto strata of the central trough in the St. Elmo area, but it is likely that these strata are sandier and thicker than at St. Elmo CH (higher on the monocline) and Genesee EH (farther up the central trough).

Repetto strata thin to the north of St. Elmo CH (cross section C-C', Plate 4), indicating significant syndepositional growth on the broad monoclinal uplift. At Union CH-20, a very thin, fine-grained section of upper, middle and lower Repetto rests on
Delmontian strata that are folded to a slightly overturned geometry in Union CH-20, R/D-1. With constrains from thicknesses, dips, and data along strike, the interpretation shown on cross section C-C' is an allowable interpretation, and it is the one that seems to fit the data the best. This interpretation involves reverse slip on the San Vicente fault, primarily during lower Repetto deposition. Slip on the San Vicente fault created the South Salt Lake anticline and caused uplift and folding of the lower Repetto and underlying strata. Erosion of the folded and uplifted lower Repetto and Delmontian strata occurred prior to middle Repetto deposition, creating an angular unconformity. Slip on the San Vicente fault slowed or stopped after lower Repetto deposition, and uplift on the larger-scale monocline continued through the rest of the Pliocene. This geometry is similar to that depicted on cross section B-B' (Plate 3) near Seibu CH, where slip on the San Vicente fault was during the mid-middle Repetto. The difference in timing of slip on the San Vicente fault, between the East Beverly Hills area (cross section B-B') and the St. Elmo area (cross section C-C'), can be explained in two ways. (1) Slip in the East Beverly Hills area occurred later (mid-middle Repetto) than at the St. Elmo area (upper-lower Repetto). (2) If middle Repetto strata, rather than lower Repetto strata, rest on Delmontian strata in Union CH-20 (cross section C-C', Plate 4), slip on the San Vicente fault would have been in the middle Repetto, like in cross section B-B'. The paleo in Union CH-20 indicates (somewhat ambiguously) that lower Repetto strata are present.

The Repetto strata originally thinned to zero north of Union CH-20, but evidence of this northern basin margin has been removed by post-Pico erosion. The Repetto strata are very thin in Union CH-20, suggesting that they originally thinned to zero just north of Union CH-20. The southernmost extent of this unconformity, where Quaternary marine gravels rest directly on Repetto strata, is shown on the Repetto isopach map (Plate 14) by the wavy line.

Summary of St. Elmo area Pliocene structural evolution

The dominant Pliocene structure in the St. Elmo area is the monoclinal uplift, which affected both Pico and Repetto deposition. At near-surface depths, most of the slip associated with the deep, monocline-causing fault has been distributed into the monoclinical fold. Some of the slip on the deep fault, however, is transmitted to the near-surface on the San Vicente fault, whose dip is very close to that of the deeper fault. The
near-surface slip on the San Vicente fault caused the localized Salt Lake anticline to form as a secondary feature on the primary monoclinal uplift.

The St. Elmo area has no secondary anticline/syncline pair, such as the East Beverly Hills or Las Cienegas fold. The simple monoclinal structure represents relative subsidence and convergence between the central trough and the monoclinal high. The stratigraphy of the East Beverly Hills area and St. Elmo area are similar, so cross section C-C' (Plate 4) could be considered a type section of the Pliocene monocline, without most of the secondary structures of the East Beverly Hills area.

The East Beverly Hills anticline allowed excess bed length to be taken up in a rabbit-ear fold. There is no secondary structure taking up excess bedding length on cross section C-C' (Plate 4). Just east of cross section C-C' is the western end of the Las Cienegas anticline, which may also accommodate excess bed length. Cross section C-C' shows neither anticline, partly because it was constructed about 20° away from dip direction, due to the location of data. If C-C' could be constructed directly across strike (~N30E) it would cross the eastern end of the East Beverly Hills anticline and the western end of the Las Cienegas anticline. Cross section C-C' is in the exact location where one fold is dying and the other is beginning.
LAS CIENEGAS AREA

Stratigraphy

The Las Cienegas area can be divided into three major regions: (1) the central trough; (2) the Las Cienegas anticline/syncline; (3) the larger-scale monoclinal high to the north, where there are no Pliocene strata. The Pico strata in the Las Cienegas area are a southward-thickening sequence of fine-grained marine sediments that are more variable than the Pico strata of the East Beverly Hills and St. Elmo areas. On average, the Pico strata on the Las Cienegas anticline and syncline are primarily claystone (90%) with interbedded siltstone (5%) and sandstone (5%), as shown on Figure 4.7. The rhythmic pattern characteristic of electric logs in the East Beverly Hills area is not present, and large- and small-scale features of electric logs are difficult to correlate between drill sites of the Las Cienegas area. Unconformities are present locally within the middle and lower Pico strata, indicating localized relative uplift. The coarsening-upward sequence of the uppermost Pico, with the characteristic funnel-shaped electric log pattern, is present throughout the Las Cienegas area.

On the Las Cienegas anticline and syncline, the early Pliocene Repetto strata are more variable and, on average, finer grained than in the East Beverly Hills area. In some areas, the lithologies are very similar to Pico strata (claystone/siltstone with secondary sandstone interbeds). In other areas, sandstone packages (generally <50 ft, or <15 m thick) locally have up to 80% sandstone, with 20% claystone/siltstone. On average, the Repetto strata on the Las Cienegas anticline and syncline have ~10% sandstone interbeds, as shown on Figure 4.7. Electric logs of Repetto strata on the Las Cienegas anticline and syncline are difficult to correlate between some drill sites, making paleo data important in correlation. Unconformities are present locally within the upper and middle Repetto strata, indicating localized relative uplift. The Repetto strata thicken and coarsen southward into the central trough.

Variations in thickness and lithology of the Pico and Repetto strata yield clues to the structural history of the Las Cienegas area. The Pico and Repetto strata vary considerably over time and distance, suggesting that the environment of deposition was affected by active structures. Variations in thickness of the Pico and Repetto can be seen on cross sections D-D', E-E', and F-F' (Plates 5, 6, and 7), and on isopach maps of the Pico and Repetto (Plates 13 and 14). Variations in lithology of the Pico and Repetto
Figure 4.7. Electric log of Pliocene strata, Texam U-19-1, Las Cienegas area. Well depths labeled at 1000-foot intervals, with ticks at 100-foot intervals. Lithologic information is given in 10% increments, averaged from mud logs from wells in the Las Cienegas area. Qmg = Quaternary marine gravels; Res. = resistivity; SP = spontaneous potential.
strata can be seen on cross sections D-D', E-E', and F-F' (Plates 5, 6, and 7), which show Pliocene sandstones from electric logs and mud logs.

**Timing of Pico structures, based on thickness and lithology**

The isopach map of Pico strata (Plate 13) shows thickening southward in the Las Cienegas area from 0 ft (0 m) in the north to ~7000 ft (~2135 m) in the central trough. This suggests that deposition of Pico strata was largely controlled by relative subsidence between the monoclinal high to the north and the central trough to the south. During deposition of the Pico strata, relative subsidence of the central trough produced an active syncline with topographic relief, which resulted in ponding of sand. Mud logs from Pacific Telephone CH and Dublin CH (cross section E-E', Plate 6) indicate that the Pico strata in the central trough have more interbedded sandstones than the Pico strata to the north (e.g. 4th Avenue drill site). Sandstone interbeds in the central trough comprise up to 70% of Pico strata locally (shown on cross sections), with an average of ~10% in the upper and upper-middle Pico and ~30% in the lower-middle and lower Pico. This contrasts with the typical Pico strata from the slope of the gentle monocline, which generally include 0%, and locally 10% sandstone interbeds. These central trough Pico strata are similar to the Pico strata in the central trough of the St. Elmo area, and coarser grained than the Repetto strata in the central trough of the East Beverly Hills area.

The monoclinal southward-thickening trend in the Las Cienegas area Pico strata is interrupted by the Las Cienegas anticline and syncline. The Pico isopach map (Plate 13) shows that the Pico thickness in the Las Cienegas syncline is 800 - 1000 ft (250 - 300 m), with 300 - 600 ft (90 - 180 m) over the anticline. Therefore, ~500 ft (~150 m) of relative subsidence occurred between the Las Cienegas anticline and syncline during Pico deposition, which is minor compared to the ~7000 ft (~2135 m) relative subsidence associated with the larger-scale monoclinal uplift. Pico folding of the Las Cienegas anticline and syncline can also be seen on the structure contour map of the Pico - Repetto contact (Plate 8). From west to east, the Las Cienegas syncline changes from a narrow, tight fold with steep limbs on cross section D-D' (Plate 5) to a wide, gentle fold at cross section F-F' (Plate 7). This eastward broadening, which is obvious on the Pico isopach map (Plate 13), is caused by the eastward divergence of the west-trending monoclinal high and the northwest-trending Las Cienegas fault and anticline.
Evidence of Las Cienegas folding during Pico deposition is variable on the cross sections in the Las Cienegas area. The cross sections will be discussed from west to east (D-D' on Plate 5; K-K' on Fig. 4.8; E-E' on Plate 6; F-F' on Plate 7). On cross section D-D' (Plate 5), the geometry of the Las Cienegas syncline is unconstrained, and is drawn primarily from constraints on cross section K-K' (Fig. 4.8; located between D-D' and E-E' - see Fig. 4.2), and from constraints on structure contour maps. Upper Pico strata rest on middle Repetto strata at the PE drillsite (D-D') and in several wells on cross section K-K' (Fig. 4.8), indicating relative uplift during the middle and lower Pico. On cross section K-K', data from Union CH-12 indicate that the Las Cienegas fold was active at least into the upper Pico, which thins over the Las Cienegas anticline and thickens slightly in the Las Cienegas syncline. The basal upper Pico dips gently north in Union CH-12 (Fig. 4.8) and filled the active syncline with strata that are sandier than the Pico section of Union CH-5 to the south and Union CH-4 to the north. The overlying upper Pico strata dip gently to the south and are not sandy, indicating that the Las Cienegas syncline was no longer topographically low. It seems unlikely that the upper Pico would rest unconformably on lower Pico in the Las Cienegas syncline (Union CH-12; Fig. 4.8), because this would require the Las Cienegas syncline to be active and subsiding in the lower Pico, uplifting/eroding in the middle Pico, and actively subsiding again in the upper Pico. Cross sections to the east show a complete section of upper, middle and lower Pico in the syncline, suggesting the possibility that the paleo samples missed the middle Pico in Union CH-12. The missing middle Pico would therefore be the upper part of the lower Pico or the lower part of the upper Pico that is shown on cross section K-K' (Fig. 4.8). The latter interpretation would mean that the north dips of the basal upper Pico (as drawn) would really be middle Pico dips, indicating that the youngest folding of the Las Cienegas syncline occurred in the middle Pico. The Las Cienegas anticline and syncline do not seem to fold the base of the Quaternary marine gravels, but a very gentle fold would be difficult to recognize in our data.

To the east is cross section E-E' (Plate 6), through the 4th Avenue drillsite. The Las Cienegas syncline is noticeably broader and gentler than farther west. The dip data and Pico contacts at the 4th Avenue drillsite and Union CH-25 indicate that the middle and lower Pico strata must form a gentle syncline in the Las Cienegas syncline. On cross section F-F', through the Murphy drillsite, the lower Pico strata are deflected downward, but do not form a syncline, because there are no north dips. The lower Pico strata are near-horizontal at the bottom of Union CH-6 (cross section F-F'; Plate 7).
Figure 4.8. Cross section K-K' through Dublin CH and Washington Blvd. EH, Las Cienegas area. This cross section has constraints at the lower Pico unconformity over the Las Cienegas anticline, and in the Las Cienegas syncline. Sandstones increase into the central trough. Location of cross section (between D-D' and E-E') is shown on Fig.4.2.
Union CH-6 is located in a broad flat area just east of the end of the Las Cienegas syncline on the structure contour map of the Pico - Repetto contact (Plate 8). The upper Pico strata, which were folded into a gentle syncline on cross section K-K', are deflected downwards but do not form a syncline on cross section E-E', and are not deflected downward on cross section F-F'. Synclinal folding of the Pico - Repetto contact (cross sections D-D', K-K' and E-E') extends farther east, and dies out near cross section F-F'.

At the Pico - Repetto contact, the crest of the Las Cienegas anticline (defined as the part of the fold with the greatest unconformity) is located south of the highest point on the Las Cienegas anticline (PE drill site on D-D', 4th Avenue drill site on E-E', Murphy drill site on F-F'). On all four cross sections (including K-K'), the lower Pico strata are completely missing on the crest of the Las Cienegas anticline, as indicated by the dotted-line pattern on the Pico isopach map (Plate 13). The middle Pico strata are extremely thin and locally missing. Thinning of the lower and middle Pico strata resulted primarily from syndepositional thinning due to a topographic high, rather than post-depositional erosion. During lower Pico deposition, the Las Cienegas anticline must have had significant uplift and topographic relief, resulting in zero deposition of lower Pico strata and erosion into the underlying Repetto strata on the crest of the anticline (shown schematically on Fig. 4.9b). The middle Pico strata in Dublin CH (OH; cross sections K-K', D-D') show extreme thickening to the south, with a dramatic change in dips from the lowest to highest middle Pico strata. The middle Pico strata below 4000 ft well depth (Dublin CH, OH) have steep south dips similar to Repetto dips, indicating that the lower-middle Repetto strata have been folded and uplifted by the Las Cienegas anticline (Fig. 4.9b). The lower-middle Pico strata (and sandstone interbeds) thin from ~2000 ft (~610 m) in the central trough to zero on the crest of the Las Cienegas anticline. The strata above ~4000 ft well depth (Dublin CH, OH) have gentle south dips similar to the dips of the overlying strata, indicating that these upper-middle Pico strata were affected by the monoclinal uplift, but not the Las Cienegas

Figure 4.9. Schematic showing the structural evolution of the Las Cienegas anticline during the Pliocene, at the position of cross section E-E' (Plate 6). Figure on next page. (a) Geometry during upper Repetto deposition. (b) Geometry during mid-middle Pico deposition. The upper Repetto geometry of the Las Cienegas anticline is shown with dotted lines. A marker bed within the middle Pico is shown for reference in (b) and (c). (c) Geometry at the end of middle Pico deposition.
Figure 4.9 (continued).
anticline (Fig. 4.9c). The geometry of the lower and middle Pico strata indicates that uplift on the Las Cienegas anticline occurred primarily during the lower and lower-middle Pico.

The lower Pico unconformity, which was near-horizontal when it formed (Fig. 4.9a), is tilted about 30° to the south. This tilting began during deposition of the upper-middle Pico. Upper-middle Pico strata thicken gently to the south, covering the lower Pico unconformity, as shown on cross sections K-K' (Fig. 4.8) and E-E' (Plate 6), and schematically on Figure 4.9c. The southward tilting of the lower Pico unconformity continued during deposition of the upper Pico strata, which thicken to the south. The southward tilting, which occurred during and after the middle Pico, mostly took place after folding of the Las Cienegas anticline and syncline, and was caused by uplift on the larger-scale monoclinal structure that was present throughout the Pliocene.

The Pico strata thin to the north of the Las Cienegas syncline, indicating significant syndepositional growth on the broad monoclinal uplift, as mentioned above. It is not possible to determine where the Pico strata originally thinned to zero at the Pico northern basin margin, because the evidence has been removed by post-Pico erosion. The post-Pico erosion is constrained on cross sections by data from Metro Rail boreholes (D-D', CEG-17; E-E', CEG-16; F-F', CEG-15; locations of CEG boreholes shown on Plate 8 and Fig. 4.2), which all have diatoms from the latest Miocene, equivalent to the Delmontian benthic foram stage (J. Barron, pers. comm., 1993). North of Union CH-4 (cross sections D-D' and K-K') and Union CH-22 (cross section E-E'), where the Pico section is only ~500 ft (~150 m) thick, the Quaternary marine gravels rest unconformably on successively older Pico strata. The southernmost extent of this unconformity is shown on the Pico isopach map (Plate 13) by the wavy line. This unconformity was caused by Quaternary uplift of the Wilshire arch (Chapter 2).

Timing of Repetto structures, based on thickness and lithology

The isopach map of Repetto strata (Plate 14) shows thickening southward in the Las Cienegas area from 0 ft (0 m) in the north to ~5000 ft (~1525 m) in the central trough. Deposition of Repetto strata was largely controlled by relative subsidence between the monoclinal high to the north and the central trough to the south. Relative subsidence of the central trough produced an active syncline with topographic relief,
which resulted in ponding of sand. Mud logs from Pacific Telephone CH and Dublin CH (cross section E-E', Plate 6) indicate that the Repetto strata in the central trough have more interbedded sandstones, including local pebbly sandstone, than the Repetto strata to the north (e.g. 4th Avenue drill site). Sandstone packages in the central trough include up to 90% sandstone locally (shown on cross sections), with an average of ~30% sandstone in the upper Repetto, ~40% in the middle Repetto, and ~50% in the lower Repetto. This contrasts with the typical Repetto strata from the Las Cienegas anticline and syncline, which average 10% sandstone interbeds (Fig. 4.7). The central trough Repetto strata of Pacific Telephone CH and Dublin CH are similar to the Repetto strata in the central trough of the St. Elmo area, and coarser grained than the Repetto strata in the central trough of the East Beverly Hills area.

The Repetto monoclinal southward-thickening trend in the Las Cienegas area is interrupted by the Las Cienegas anticline and syncline. The Repetto isopach map (Plate 14) shows that the Repetto thickness over the Las Cienegas anticline is ~500 ft (~150 m), with up to 1400 ft (425 m) in the syncline. Therefore, ~750 ft (~230 m) of relative subsidence occurred between the Las Cienegas anticline and syncline during Repetto deposition, which is minor compared to the ~5000 ft (~1525 m) of relative subsidence associated with the monoclinal uplift. Repetto folding of the Las Cienegas anticline and syncline can also be seen on the structure contour map of the Repetto - Delmontian contact (Plate 9). From west to east, the Las Cienegas syncline changes from a narrow, tight fold with steep limbs on cross section D-D' (Plate 5) to a wide, gentle fold at cross section F-F' (Plate 7). This eastward broadening, which is obvious on the Repetto isopach map (Plate 14) and on the structure contour map of the Repetto - Delmontian contact (Plate 9), is caused by the eastward divergence of the west-trending monoclinal high and the northwest-trending Las Cienegas fault and anticline.

Evidence of folding of the Las Cienegas anticline and syncline during Repetto deposition is best observed on cross sections, which will be discussed from west to east (D-D' on Plate 5; K-K' on Fig. 4.8; E-E' on Plate 6; F-F' on Plate 7). On cross section D-D' (Plate 5), the geometry of the Las Cienegas syncline is unconstrained, and is drawn primarily from constraints on cross section K-K' (Fig. 4.8; located between D-D' and E-E' - see Fig. 4.2), and from constraints on structure contour maps. On cross section K-K' (Fig. 4.8), upper Pico strata rest on middle and upper Repetto strata with an angular unconformity at Washington Blvd. EH and Union CH-21. An angular unconformity is also inferred in the area between Union CH-5 and Union CH-12 (Fig. 4.8). The presence of the angular unconformity indicates that a major phase of uplift
on the Las Cienegas anticline (during the lower and lower-middle Pico, as discussed above) occurred after deposition of the middle and upper Repetto (shown schematically on Fig. 4.9b). Upper and upper-middle Pico strata also rest, with angular unconformity, on middle and upper Repetto on cross sections E-E' and F-F' (Plates 6 and 7). On cross section K-K' (Fig. 4.8), the upper Repetto and lower Pico strata dip uniformly north in Union CH-12, indicating that these were not growth strata, which would have fanning dips due to progressive subsidence. The rest of the syncline is not directly constrained, and "best-fit" contacts were drawn based on constraints deeper in the cross section and along strike. The Repetto activity of the Las Cienegas syncline can be determined more accurately from cross sections E-E' and F-F' (Plates 6 and 7), which have better constraints in the syncline.

To the east is cross section E-E' (Plate 6) through the 4th Avenue drillsite, and cross section F-F' (Plate 7) through the Murphy drillsite. The Las Cienegas syncline is noticeably broader and gentler than farther west. The 4th Avenue and Murphy drillsites both have north dips in the Repetto strata, indicating the presence of the Las Cienegas syncline, overlain by south-dipping Pico strata. The north dips and increasing Repetto thickness at the 4th Avenue drillsite indicate that the syncline was actively subsiding as a topographic low during the upper Repetto, and to a lesser degree, during the middle and lower Repetto. At the 4th Avenue drillsite, a thin (∼100 ft; ∼30 m) package of sandstone-dominated strata straddles the upper-middle Repetto contact. This sandstone-dominated package thickens to ∼250 ft (∼75 m) thick in the Las Cienegas syncline, as shown on cross section E-E' (4th Avenue #7A, Union CH-25; Plate 6), and is not present at Union CH-29 to the north. The thickening of sandstone interbeds into the Las Cienegas syncline indicates that the syncline was a topographic trough during Repetto deposition. On cross section F-F' (Plate 7), the same sandstone-dominated package is only ∼40 ft (∼12 m) thick at the Murphy drillsite and ∼100 ft (∼30 m) thick in Texam U-19-1 (Fig. 4.7), because the Las Cienegas syncline was broader and gentler, and dying to the east, and therefore had less topographic relief than at cross section E-E' (Plate 6).

The Repetto strata thicken south of the crest of the Las Cienegas anticline into the central trough. Part of the upper and middle Repetto strata have been eroded, but enough strata remain to interpret the structural history of this steep south limb of the Las Cienegas anticline (Fig. 4.9). Original depositional thicknesses of the upper, middle, and lower Repetto strata (estimated for the upper and middle) all increase to the south (cross sections K-K', E-E', and F-F'; Fig. 4.8, Plates 6 and 7). The major increase
in thickness and sandstone interbeds occurs just south of the crest of the Las Cienegas anticline, with very minor thickening along the south-dipping limb (cross sections D-D', K-K', E-E', F-F'; shown schematically on Fig. 4.9a). On the south-dipping limb, thickness and sandstone interbeds increase slightly into the trough, and the dip of the uppermost Repetto strata is only slightly shallower than the dip of the lowermost Repetto (cross sections D-D', K-K', E-E', F-F'). This thickness and dip geometry indicates that the south-dipping limb of the Las Cienegas anticline was originally part of a broader central trough than exists today, with gentle topography and minimal growth strata on the south side of the Las Cienegas anticline (Fig. 4.9a). The monoclinal uplift was present during Repetto deposition (Fig. 4.9a), with thin strata deposited over the Las Cienegas anticline/syncline and thick strata deposited in the wide central trough. During the lower and lower-middle Pico, this depositional pattern was disrupted by increased uplift of the Las Cienegas anticline (Fig. 4.9b). Upper-middle (Fig. 4.9c) and upper Pico strata thicken southward down the entire south-dipping limb of the monoclinal uplift, due to southward monoclinal tilting with only minimal uplift of the Las Cienegas anticline. The Pico southward tilting also affected the underlying Repetto strata, which are vertical to overturned in cross sections E-E' and F-F' (Plates 6 and 7). The overturned Repetto - Delmontian contact can also be seen on the structure contour map (Plate 9).

North of the Las Cienegas syncline, the Repetto strata thin to the north, indicating significant syndepositional growth on the broad monoclinal uplift, as mentioned above. It is not possible to determine where the Repetto strata originally thinned to zero at the Repetto northern basin margin, because the evidence has been removed by post-Pico erosion, allowing the Quaternary marine gravels rest unconformably on successively older Repetto strata. The southernmost extent of this unconformity is shown on the Repetto isopach map (Plate 14) by the wavy line. The post-Pico erosion is constrained on cross sections by data from the Los Angeles Metro Rail boreholes (D-D', CEG-17; E-E', CEG-16; F-F', CEG-15; locations of CEG boreholes shown on Fig. 4.2 and Plate 8), which all have diatoms indicating a latest Miocene age (J. Barron, pers. comm., 1993). Union CH-4 (cross sections D-D' and K-K') has no lower Repetto strata, indicating that these strata onlapped the edge of the monoclinal high.
Summary of Las Cienegas area Pliocene structural evolution

The dominant Pliocene structure in the Las Cienegas area is the monoclinal uplift, which affected both Pico and Repetto deposition. The relative subsidence associated with the monoclinal structure during the Pliocene was greater than the relative subsidence associated with the Las Cienegas fold. The monocline originated near the time of the Repettian - Delmontian contact, because the Delmontian strata do not show any substantial southward thickening (Plate 15). Relative monoclinal subsidence was greater during Pico deposition (~7000 ft, ~2135 m) than during Repetto deposition (~5000 ft, ~1525 m). Using the method described for the East Beverly Hills area monocline, the dip of the Monocline fault can be calculated from estimates of relative subsidence and shortening. Schneider (1994) carried out these calculations, which indicate that the Monocline fault dips north between 55° and 62°, depending on the assumptions used. This dip is essentially the same as for the Monocline fault in the East Beverly Hills area, suggesting that the fault was a through-going structure causing the Pliocene monoclinal flexure along the entire study area.

Secondary structures in the Las Cienegas areas differ from those in the East Beverly Hills area. The main reason for this difference is the Las Cienegas fault, which originated as a south-dipping normal fault in the late Miocene (Davis et al., 1989; Wright, 1991; Schneider, 1994). The Las Cienegas fault formed the southern boundary of a Miocene basement high, and was reactivated in the Pliocene as a reverse fault. This reactivation first required the fault to rotate from dipping steeply south to dipping steeply north. The monoclinal flexure, beginning in the latest Delmontian or earliest Repetto, would have caused any passive marker to rotate counter-clockwise, as viewed from the east (the same view used on the cross section). This counter-clockwise rotation tilted horizontal bedding to south-dipping, and rotated the steeply south-dipping Las Cienegas fault to steeply north-dipping. As the Las Cienegas fault achieved a steeply north-dipping orientation, it was nearly parallel to the Monocline fault. Some of the reverse slip on the deep fault was transferred to the shallower Las Cienegas fault, which localized uplift at the tip of the fault, forming the Las Cienegas anticline.

The Las Cienegas fault cuts farther upsection on cross sections E-E' and F-F' (Plates 6 and 7) than it does on cross sections D-D' and K-K' (Plate 5; Fig. 4.8), but existing data do not allow us to map the exact location of the tip of the Las Cienegas
fault. On cross sections E-E' and F-F', the Las Cienegas fault cuts part or all of the Delmontian strata, but apparently does not cut the overlying Repetto or Pico strata.

During Repetto deposition, reverse slip on the Las Cienegas fault caused localized thinning of Repetto strata over a narrow anticline (Fig. 4.9a). Simultaneous monoclinal uplift resulted in overall thicker deposition in the central trough and thinner deposition to the north. Increased reverse slip on the Las Cienegas fault during the lower Pico (also noted by Wright, 1991) caused significant uplift, which resulted in an angular unconformity between middle or upper Pico strata and middle or upper Repetto strata (Fig. 4.9b). During the upper-middle Pico, slip on the Las Cienegas fault decreased, and the monoclinal flexure caused southward tilting of strata, with southward thickening of upper-middle (Fig. 4.9c) and upper Pico strata.

North of the Las Cienegas fault is the San Vicente fault, which splits into a north and south branch between cross sections E-E' and F-F' (Plates 6 and 7). Some of the reverse slip on the Monocline fault was transmitted to the near-surface on the San Vicente fault, whose dip is very close to that of the deeper fault. A small anticlinal fold formed in the hangingwall of the San Vicente fault (two folds on cross section F-F'). This hangingwall fold is unconstrained in the Repetto and Pico section, but dip data and thicknesses in Union CH-22 (cross section E-E', Plate 6) suggest that the San Vicente fault, and its hangingwall fold, were active primarily during the lower and/or middle Repetto. This timing agrees well with the middle Repetto slip in the area of cross section B-B' (East Beverly Hills area, Plate 3) and the lower to middle Repetto slip in the St. Elmo CH area (cross section C-C', Plate 4).
HOLLYWOOD BASIN AND NORTH SALT LAKE FAULT

Just south of the Hollywood fault is the Hollywood basin, which is an active syncline filled with Quaternary marine and alluvial sand and gravel (Chapter 2). The Pliocene history of the Hollywood basin is somewhat enigmatic, due to lack of data. Three wells have been drilled in or near the Hollywood basin. The first well is Laurel CH-2 (cross section A-A'; Plate 2), where Quaternary strata rest directly on late Miocene upper Mohnian strata. There is no evidence that Pliocene strata were ever deposited at this location.

In Vista CH (cross section B-B', Plate 3), industry paleo indicates the presence of Quaternary marine gravels, middle Pico, lower Pico, upper Repetto, and Delmontian strata. This sequence suggests a lower-to-middle Repetto unconformity, which eroded the Delmontian strata to a thickness far less than is present in the East Beverly Hills area. The lack of upper Pico strata suggests another phase of uplift. The North Salt Lake fault, discussed by Wright (1991), cuts Vista CH in two places, allowing us to establish an apparent fault dip of ~55°, within the plane of the cross section. The North Salt Lake fault has normal separation in cross section B-B' (Plate 3).

In Hollywood CH (cross section F-F', Plate 7), two versions of industry paleo are contradictory. One set of paleo picks (shown on cross section F-F') indicates that upper Pico rests on middle Repetto, which rests on Delmontian strata. Another set of paleo picks indicates that there are no Pico strata, and Repetto (undifferentiated) rests on Delmontian. In either interpretation, the sequence of strata present in Hollywood CH is different from the sequence present in Vista CH to the west. The North Salt Lake fault cuts Hollywood CH in three places, allowing us to establish an apparent fault dip of ~60°, within the plane of the cross section. The five fault cuts (two in Vista CH; three in Hollywood CH) allow us to determine the fault's strike and dip (the fault dips ~60° toward N30W, see Plate 12) between the depths of ~4000 ft (1220 m) and ~2000 ft (610 m).

There are no data to constrain the dip of the fault shallower than ~2000 ft (610 m). There are not enough data to unravel the Pliocene history of either Vista CH or Hollywood CH, or explain why the two wells have different Pliocene strata. There are also not enough data to determine crosscutting relationships between the Pliocene strata and the North Salt Lake fault, which would allow us to establish timing and sense of
motion on the fault. Therefore, the interpretations shown on cross sections B-B' and F-F' (Plates 3 and 7) are somewhat arbitrary.

Despite this lack of data, some aspects of the North Salt Lake fault can be discussed. The North Salt Lake fault was probably active during Repetto deposition, because the Delmontian strata are offset from above ground level in the footwall, to several thousand feet deep in the hangingwall. Wright (1991) also suggested that the North Salt Lake fault may have originated at the latest Miocene to earliest Pliocene. The North Salt Lake fault was probably not a late Miocene (i.e. Delmontian) normal fault, because the hangingwall Delmontian strata are only ~500 - 700 ft (~150 - 215 m) thick, which is far too thin for these strata to be normal fault growth strata. In Hollywood CH (cross section F-F'), the lowest Repetto strata dip ~30° south, while the dip at the ?Pico - ?Repetto contact is nearly horizontal, indicating that the Repetto strata may be growth strata, possibly in the hangingwall of a normal fault. This interpretation is problematic, however, because the compressional Pliocene stress regime had approximately the same orientation as today’s stress field, with σ1 oriented towards the north-northeast (Hauksson, 1990; see Chapter 1). This would make a fault trending N60E an unlikely candidate for a Pliocene normal fault. The more likely Pliocene motion on a fault trending N60E would be oblique left-reverse slip. The normal separation of the North Salt Lake fault in Vista CH and Hollywood CH is not compatible with a reverse fault, but could result from left slip. Some combination of fault orientation, sense of slip, and magnitude of slip allowed a small Pliocene basin to form between the North Salt Lake fault and the Hollywood fault to the north, which strikes ~N75E and dips steeply north.

While North Salt Lake faulting during the Repetto is likely, faulting during the Pico is more conjectural. As drawn on cross sections B-B' and F-F' (Plates 3 and 7), the North Salt Lake fault was active during Pico deposition (assuming that the upper part of the Pliocene section in Hollywood CH is Pico). It is also possible that the Pico strata were deposited over a dead North Salt Lake fault, with the Pico basin extending south and overlapping the fault. It is not possible to distinguish between these two hypotheses based on existing data.
DISCUSSION AND CONCLUSIONS

Comparison of Pico and Repetto isopachs to regional data

In a study of the entire Los Angeles basin, Yeats and Beall (1991) presented an isopach map of the post-Repetto strata (Pico + Quaternary marine gravels + Quaternary alluvium), and an isopach map of the Repetto strata. Both regional isopach maps show a northwest-trending depocenter, located in the same position as today's subsiding central trough (see Chapter 1). The post-Repetto isopach map of Yeats and Beall (1991) shows 4000 - 7500 ft (1220 - 2290 m) of strata in the northwestern end of the central trough. This thickness agrees generally with the results presented here, which show that the northwestern end of the central trough has 4000 - 7000 ft (1220 - 2135 m) of Pico strata (Plate 13) plus 750 - 1000 ft (230 - 300 m) of Quaternary marine gravels plus Quaternary alluvium (estimated from cross sections and from Fig. 2.1). In our detailed study, presented here, the total thickness of post-Repetto strata is 5000 - 8000 ft (1525 - 2440 m), or slightly greater than the thickness presented by Yeats and Beall (1991). Yeats and Beall (1991) also show that the Las Cienegas fault cuts the post-Repetto strata, which is not true for the western part of the Las Cienegas fault, studied in detail here.

The Repetto isopach map of Yeats and Beall (1991) shows 4000 - 5500 ft (1220 - 1680 m) of Repetto strata in the northwestern end of the central trough. This thickness agrees well with the results presented here, which show that the northwestern end of the central trough has 4000 - 5000 ft (1220 - 1525 m) of Repetto strata (Plate 14). In our detailed study presented here, the location of the isopach lines is refined, and the northwestern end of the central trough extends farther than Yeats and Beall (1991) indicate. Yeats and Beall (1991) also show that the Las Cienegas fault cuts the Repetto strata, which is not true for the western part of the Las Cienegas fault, studied in detail here.

Dating of the Metro Rail samples

We arranged for access to samples from Metro Rail borings (CEG 15 - CEG 23; locations shown on Fig. 4.2 and on Plate 8) from Converse Consultants (Pasadena,
The shallow borings all penetrate Tertiary marine strata, which are overlain unconformably by Quaternary marine gravels. Benthic forams from nine samples were identified and analyzed by Mary Lou Cotton (Bakersfield, CA) and later corroborated by Kris McDougall (USGS, Menlo Park). Five of the nine samples (from CEG 16, 18, 20, 21, and 22) had benthic foram assemblages indicating the Wheelerian (middle Pico) or Venturian (lower Pico) benthic foram stage. The other four samples were nondiagnostic.

Examination of the sample material by Dan Ponti (USGS, Menlo Park) also revealed three small ash beds, in CEG 16 and CEG 18. Glass shards from the ashes were subsequently correlated by Andrei Sarna-Wojcicki (USGS, Menlo Park) to latest Miocene (or earliest Pliocene?) ashes. Fission-track dating on glass (Nancy Naeser, USGS, Denver) is planned but there are no results at present. These results indicate a significant age discrepancy between the benthic foram "ages" (lower to middle Pico is ~1.5 - 2.5 Ma; Blake, 1991) and the ash ages (5.5 - 4.3 Ma).

Another approach to dating the Metro Rail samples was to have the diatoms identified and analyzed by John Barron (USGS, Menlo Park). The results, mentioned earlier in this chapter, indicate that boreholes CEG 15 - 19 and CEG 23 all have diatoms that indicate a latest Miocene (Delmontian equivalent) age. CEG 20 - 21 were barren of diatoms, and CEG 22 diatoms were nondiagnostic. The latest Miocene diatom ages corroborate the latest Miocene ash ages, and contradict the apparent middle Pliocene benthic foram "ages". Some of the implications of these age discrepancies are presented in Ponti et al. (1993).

The ash and diatom ages suggest that the "Pico" benthic forams really are latest Miocene in age, but have the species assemblage expected in a middle Pliocene benthic foram stage. Many workers have recognized that benthic foram stages can be time-transgressive (see Chapter 1), but a time-transgression of 3 Ma is unprecedented in the Los Angeles basin. Natland (1952) noted that near basin margins, one should expect younger-appearing benthic foram stages in older rocks. This situation exists in the Metro Rail borings, where Pico-appearing forams are present in latest Miocene rocks. It is interesting to note that the water depth for Delmontian forams (upper to middle bathyal; Blake, 1991) overlaps the water depth for lower to middle Pico forams (middle bathyal; Blake, 1991). Distinguishing Delmontian forams from Pico forams is based on: (1) the expected presence of the intervening lower bathyal Repetto forams, and (2) the presence of forams that have become extinct since the latest Miocene. In the case of the Metro Rail samples, there are no intervening Repetto strata present, and the
diagnostic extinct late Miocene forams are not present. The lack of extinct late Miocene forams may be due to the small number of samples analyzed, although it is surprising to have no late Miocene forams in nine samples. Alternatively, the latest Miocene environmental conditions may have favored the Pico-appearing forams but not the now-extinct forams.

The apparent age discrepancy between the benthic forams and other dating methods is a reminder that benthic forams stages are only environmental indicators and may be time-transgressive (see Chapter 1). In our study area, the age problem seems to be confined to the Metro Rail boreholes, most of which were drilled at the edge of the monoclinal high. At this position, there are no diagnostic Repetto forams to help distinguish Delmontian from Pico forams. In most of the northern Los Angeles basin study area, there is a complete section of Mohnian, Delmontian, Repetto (lower, middle and upper) and Pico (lower, middle, and upper) strata. Most of these strata (including a double-bentonite at the Mohnian - Delmontian contact, smaller bentonites in the Repetto, and turbidite packages) can be correlated over large parts of the study area, and are therefore not significantly time transgressive. In much of the study area, the Repetto strata are present, which precludes the possibility of mistaking Delmontian forams for Pico forams.

Timing of beginning of Pliocene compression

Based on the distribution, thickness, and lithology of strata in the northern Los Angeles basin, the entire Repetto and Pico were characterized by compression. The distribution of upper Delmontian sandstones in the East Beverly Hills area indicates that compression (folding of the East Beverly Hills anticline and syncline) began during the latest Delmontian. The initiation of compression can also be estimated based on the bed lengths of successive stratigraphic contacts. In a compressional regime with growth strata, younger horizons have shorter bed lengths than older horizons, which have experienced more folding than the younger strata. A glance at any of our cross sections (Plates 2 through 7) shows that the length of the Pico - Repetto contact is shorter than the length of the Repetto - Delmontian contact. During an extensional regime, younger horizons have longer bed lengths than older horizons, which have been extended to match the progressively younger and longer bed lengths.
A bed length comparison (Fig. 4.10) was made for cross section C-C' (Plate 4), which is in the transitional area between the East Beverly Hills and Las Cienegas areas. The bed lengths show a clear pattern that corroborates the structural history interpreted from the thickness and lithology of strata. Figure 4.10 shows that the Pliocene compressional regime began in the late Delmontian (~5 Ma), and the late Miocene extensional regime had ended by the Delmontian (~7 Ma; Chapter 1; Schneider, 1994). The bed length at the Repetto - Delmontian contact was arbitrarily assigned a value of 100% bed length, for comparison. The longest bed length occurs in lower to middle Delmontian strata, which were deposited after the late Miocene extensional period had ended, but before the Pliocene compressional period began. The paleo data and electric logs do not allow extensive correlation of any intra-Delmontian horizon that would further constrain the time that compression began.

The conclusion that we are able to make, based on thickness, lithology, and line length, is that compression began in the northern Los Angeles basin around ~5 Ma, during deposition of the upper Delmontian. This estimate allows for refinement of the simplification made by Davis et al. (1989) and Hauksson (1990), who stated that compression began at some time during the Repetto, between 2.2 and 4.0 Ma.
Figure 4.10. Graph of bed lengths of major stratigraphic contacts over time. Bed lengths were measured along cross section C-C' (Plate 4). Bed length of Repetto - Delmontian contact is assigned a value of 100%, with the other measurements normalized to this measurement. Successive increase in Miocene bed length indicates extensional normal faulting. Successive decrease in Pliocene bed lengths indicates shortening associated with compressional folding and reverse faulting. Dashed line is a possible projection of the data to determine timing of maximum bed length and initiation of convergence and shortening. Ages of contacts after Blake (1991).
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