UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Summary of Geology and Petroleum Plays Used to Assess Undiscovered Recoverable Petroleum Resources of Los Angeles Basin Province, California

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TABLE OF CONTENTS

FIGURES

TABLES

INTRODUCTION

During 1987 the Geological Survey conducted an assessment of the undiscovered recoverable petroleum resources of the Los Angeles basin province, California, as part of a national assessment (Mast and others, 1988). This report describes the petroleum plays designed to assist in this assessment, and briefly summarizes the geology and petroleum development of the Los Angeles basin province. For purposes of this assessment, the Los Angeles basin province includes the area (1) south of a line that connects exposures of basement rocks in the Santa Monica Mountains, San Rafael Hills and San Gabriel Mountains and (2) west of a north-south line that extends from the eastern San Gabriel Mountains southward through Corona and thence southeastward around the western edge of exposures of basement rocks in the western Santa Ana Mountains to the coast at San Mateo Point (fig. 1). The southwest limit of the province is the boundary between state and federal jurisdiction three nautical miles from shore on the inner continental shelf in the Pacific Ocean (fig. 1). As defined above, the Los Angeles basin province covers about 4,900 km^2 (1,900 mi^2), and contains about 16,000 km^3 (3,900 mi^3) of sedimentary rock (Varnes and Dolton, 1982).

The more restricted Los Angeles basin, as distinct from the Los Angeles basin province, is estimated to cover about 3,860 km^2 (1,490 mi^2), and contain about 15,400 km^3 (3,695 mi^3) of sedimentary rock (T. H. McCulloh, personal communication, 1975; McCulloh and others, 1978). Barbat (1958) estimated a volume of 6,670 km^3 (1,600 mi^3), which Wright (1987b) revised to 8,335 km^3 (2,000 mi^3), "for the drainage area of the basin oil fields", taken to be between the Whittier and Palos Verdes Hill fault zones (fig. 1). This area is too restricted for the Neogene Los Angeles basin, even if outlying areas are excluded, although most of the petroleum generation probably came from this volume of rocks.

GEOLOGICAL SUMMARY

Previous Work

The Los Angeles basin is one of the more thoroughly studied basins in the U.S., and many important studies of the region and its tectonic setting have been published. A selection of important papers through 1962 is given by Yerkes and others (1965). Some of the more important studies of broad scope since 1962 include Durham and Yerkes (1964), Yerkes and others (1965), Yerkes and Campbell (1971), Gardett (1971), Hill (1971), Yerkes (1972), Harding (1973), Yeats (1973), Crowell (1974), Campbell and Yerkes (1976), Nardin and Henyey (1978), and Schoellhamer and others (1981). Recent summary papers are by Schwartz and Colburn (1987) and Wright (1987b). A very large effort also has been devoted to study of the seismicity and earthquake hazards of southern California (e.g., Zioney, 1985). Many more areally or topically restricted studies have been published, and some of these are given in the reference section, including some not cited in this paper. The following geological summary is taken mostly from Yerkes and others (1965), Campbell and Yerkes (1976), Crowell (1987), Wright (1987a,b), Mayer (1987), and Schwartz and Colburn (1987).

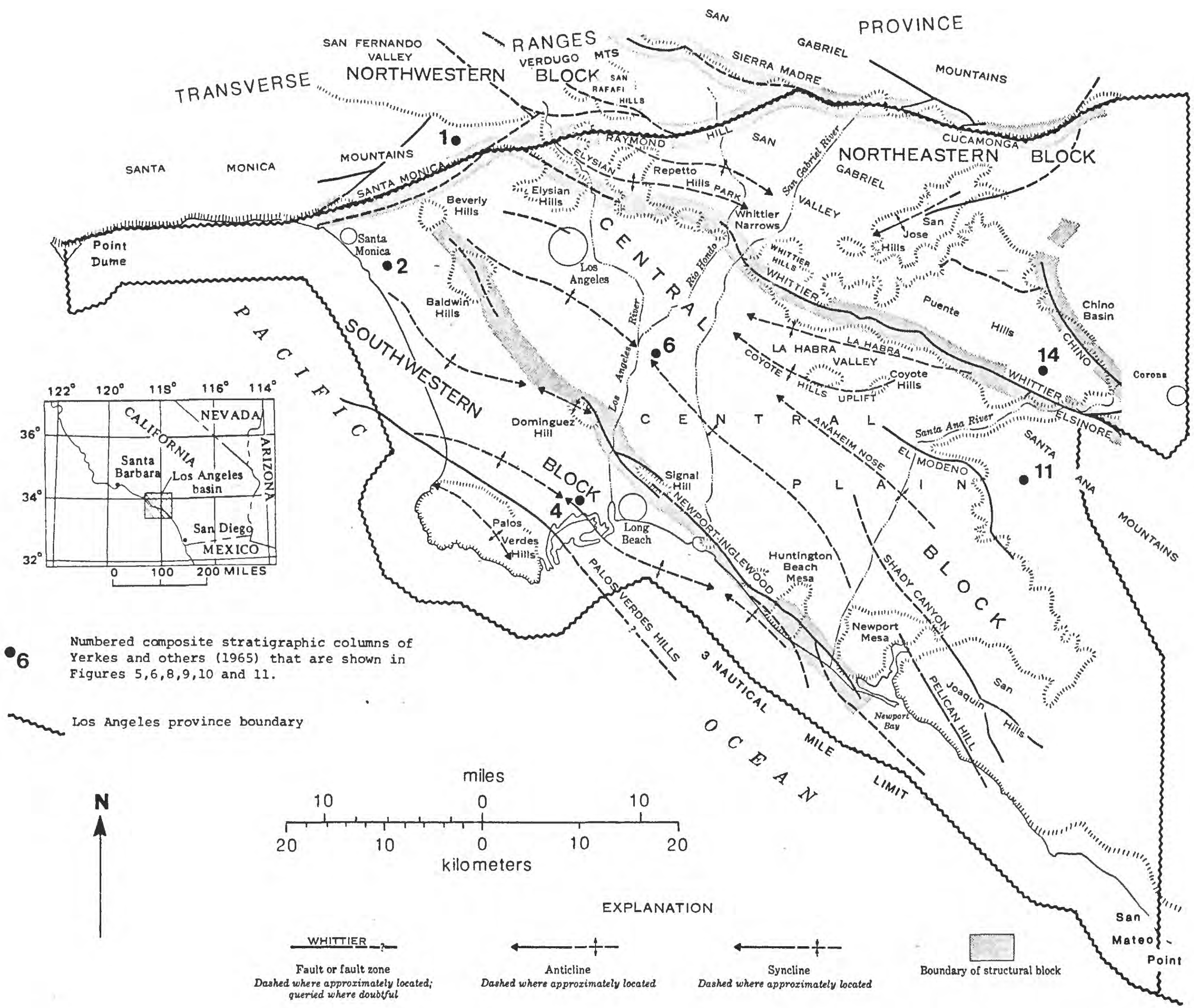

Figure 1. Index map of physiographic features, major structural features on the basement surface, four informal structural blocks and numbered locations of composite stratigraphic columns of the Los Angeles basin province of California (modified from Yerkes and others, 1965).

Tectonic History and Basin Evolution

The petroliferous Los Angeles basin is primarily a Neogene tectonic feature whose development has been a consequence of the extremely complex, late Mesozoic through Cenozoic tectonic history of southern California and the adjacent boundary areas of the North American and oceanic plates. Several general phases of tectonic development since the late Mesozoic are recognized today, although the mechanics and details continue to be debated and studied (Crowell, 1987).

Prebasin Phase

California was in a convergent margin setting caused by normal and later oblique subduction of oceanic crust beneath the western edge of North America during late Mesozoic and early Cenozoic time (Atwater, 1970; Dickinson and Seeley, 1979; Howell and others, 1980). Forearc basin sedimentary rocks deposited during this time occur in widely separated outcrops in parts of southern California and northern Baja California (Yerkes and others, 1965; Fritsche, 1973; Sage, 1975; Schoellhamer and others, 1981; Abbott, 1984). Reconstruction of Late Cretaceous paleogeography in southern California and northern Baja California suggests a west-facing part of a forearc basin, similar to but originally located south of the Great Valley sequence of central and northern California (Bottjer and Link, 1984; Fry and others, 1985).

Oblique subduction with a northerly to northeasterly convergence direction from latest Cretaceous through Paleocene or early Eocene (Engebretson and others, 1985; Page and Engebretson, 1984; Nilsen and Clarke, 1975; Dickinson and others, 1979; Bartow, 1987), while generally evident in the geologic record of central California, is less apparent in the sparse and fragmented Paleocene rocks of southern California that appear to be allochthonous, having been deposited on terrane moved northward and accreted to southern California in post-Late Paleocene time (Nilsen, 1987; Howell and others, 1987). Basal unconformities in the Santa Monica and Santa Ana Mountains suggest a period of probable vertical tectonism during Paleocene (Yerkes and others, 1965; Vedder, 1987). Extensive deposits of Eocene rocks onshore and offshore southern California indicate continued or renewed, largely progradational sedimentation in a west-facing forearc basin, although these rocks apparently also were deposited on allochthonous terrane moved northward and accreted to southern California after Eocene and before the end of Miocene (e.g., Howell and Link, 1979; Howell and others, 1980; Nilsen, 1987; Howell and others, 1987; Vedder, 1987).

When the easternmost part of the spreading center of the East Pacific rise encountered the subduction zone at the central California margin in mid-Oligocene time, paired triple junctions formed and moved away from one another along a northwest-southeast trending transform (Atwater and Molner, 1973) (fig. 2). The southeastward-moving junction, called the Rivera triple junction, is presumed to have passed by southern California on the west approximately during early Miocene, introducing a right-lateral transform phase of tectonism to southern California (Blake and others, 1978; Howell and others, 1980; Vedder, 1987). Oligocene through lower Miocene nonmarine to shallow-marine rocks exposed intermittently in clockwise fashion from the northwest to southeast margins of the Los Angeles basin, and present in the subsurface of the northern and eastern parts of the basin (Yerkes and others, 1965),

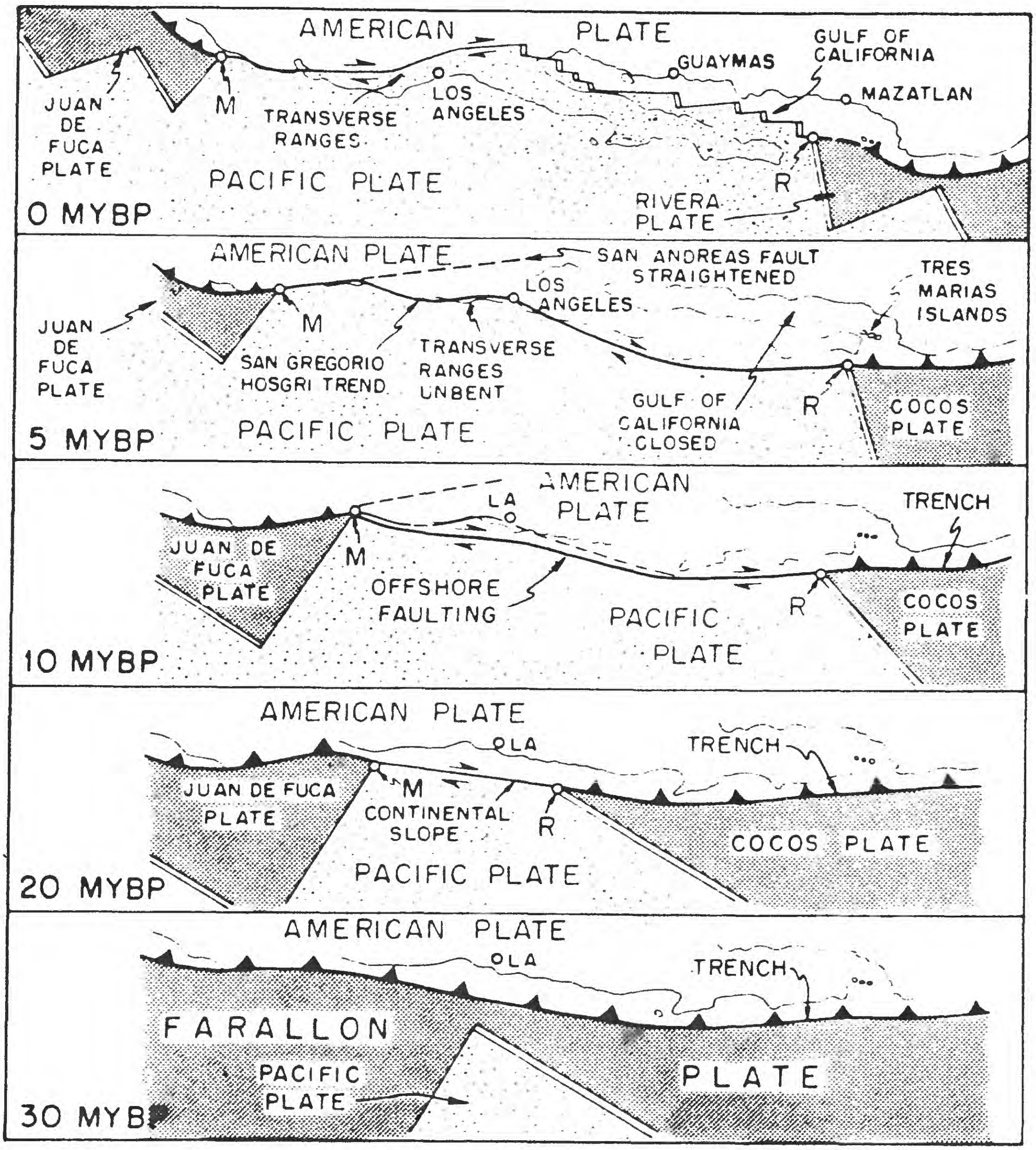

Figure 2. Sequential evolution of the California portion of the North American and Pacific plates boundary during the past 30 million years (since mid-Oligocene time) (Dickinson, 1981). Note migratory Mendocino (M) and Rivera (R) triple junctions. LA = Los Angeles.

represent a late Oligocene low-stand of sea level and possibly the earliest stage of regional uplift, faulting and subsidence caused by this new transform regime (Yerkes and others, 1965; Ingle, 1973; Crowell, 1974; Truex, 1976; Yerkes and Campbell, 1979; Schoellhamer and others, 1981; Nilsen, 1984; Mayer, 1987).

Basin Phase

The major period of tectonism that commenced in southern California during the Miocene was well documented long before the exposition of the plate tectonic history of the western margin of North America (e.g., Jahns, 1954; Barbat, 1958). However, the causes and nature of this tectonism remained unexplained until the plate tectonic history of the California margin began to unfold (e.g., Yeats, 1968; Hamilton, 1969; Atwater, 1970). Today the origin and Neogene development of Los Angeles basin is best explained as the product of transform tectonism that commenced during Early Miocene time and has continued with evolving impact to present-day (e.g., Yerkes and Campbell, 1971; Campbell and Yerkes, 1971; Crowell, 1974; Campbell and Yerkes, 1976; Yeats, 1978; Howell and others, 1980).

There is much geologic evidence for tectonic activity during the inception and early history of the Los Angeles basin from middle Early Miocene to early Late Miocene (about 21 Ma to 10 Ma). A marine transgression during which subsidence rates progressively exceeded sedimentation rates is evidenced from the transition of littoral and sublittoral to bathyal fossils in progressively younger late Early to early Middle Miocene strata (e.g., Natland, 1957; Ingle, 1972). Subsidence rates that locally resulted in upper bathyal, oxygen-poor biofacies as early as the beginning of Middle Miocene time were widespread throughout the basin later in early Middle Miocene. Early Middle Miocene to early Late Miocene marine rocks were deposited over the present sites of the (1) central syncline, (2) Palos Verdes, San Jose, Puente and San Joaquin Hills, (3) Santa Monica Mountains, and (4) parts of the San Gabriel and San Fernando Valleys (Yerkes and others, 1965, figs. 9 and 10). Deposition of organic-rich sediments at bathyal or near-bathyal depths in a silled basin continued into Upper Miocene time.

Extensive igneous flows, various types of intrusive rocks, and tephra were emplaced within and around Los Angeles basin during Middle Miocene time (mostly from 16 to 12 Ma) (e.g., Woodford and others, 1954; Vedder and others, 1957; Eaton, 1958; Yerkes and others, 1965; see Schwartz and Colburn, 1987, for age summary). This period of volcanism was associated with extensional tectonism because some normal faults in the San Joaquin Hills are intruded by dikes, reactivated, and then overlapped by later middle Miocene strata (Vedder and others, 1957; Yerkes and others, 1965, p. A52; Vedder, personal communication, 1988).

A widespread Middle Miocene schist breccia, the San Onofre Breccia (Woodford, 1925), was deposited (about 16 to 13 Ma) along the mainland coast and was derived from a north-trending Middle Miocene schist basement ridge that was located off the coast to the west (Junger, 1974; Stuart, 1979). These unusual deposits are indicative of rapid differential uplift and erosion of a distinctive basement terrane (Vedder, 1987) that many investigators believe is bounded on the northeast by the Newport-Inglewood zone of deformation (e.g., Hill, 1971; Barrows, 1974). Significant dip separations along faults at the southwest margin of Los Angeles basin, possibly including the Newport-Inglewood zone, during Early and Middle Miocene must have presented the source terrane from which the San Onofre Breccia was derived. However, it remains unclear whether major right-lateral strike-slip or detachment faulting was responsible (Hill, 1971; Yeats, 1973; Platt and Stuart, 1974; Crowell, 1987; Howell and others, 1987).

Left-lateral displacement of between 60 km (37 miles) to 90 km (55 miles) on the Malibu Coast-Santa Monica-Raymond Hill-Cucamunga fault system during Middle and possibly part of Late Miocene time has been inferred from apparent offsets of early Tertiary shorelines (Yeats, 1968; Yerkes and Campbell, 1971; Sage, 1973; Campbell and Yerkes, 1976, fig. 1). Based on a general correlation of submarine fan deposits in the subsurface south of the Santa Monica fault zone with similar deposits on the north side of the Santa Monica Mountains, Wright and others (1973) concluded that Mio-Pliocene left-lateral displacement along the Santa Monica fault zone has offset these Middle Miocene rocks about 9.5 to 13 km (6 to 8 miles) (fig. 3). Lamar (1961) concluded that post-Miocene left-lateral displacement along the Santa Monica fault was 11 km (7 miles).

Uplift of nearby source terranes occurred in Early Miocene, based on changes in the provenance from lower Tertiary to Early Miocene rocks in the northern Santa Ana Mountains (Schoellhamer and others, 1981). Elsewhere around the margins of the basin, numerous faults, unconformities, and rapid changes in facies attest to the tectonic unrest during Middle Miocene time (Yerkes and others, 1965).

Middle Miocene tectonism has been attributed to crustal extension, stretching and rifting, and to translation and(or) differential rotation of crustal blocks (e.g., Yeats, 1968; Campbell and Yerkes, 1971; Yerkes and Campbell, 1971; Crowell, 1974; Campbell and Yerkes, 1976; Kamerling and Luyendyk, 1979; Link and others, 1984; Hornafius and others, 1986; Howell and others, 1987). The several thoughtful models of Neogene paleogeography explain some of the geologic observations, but none is entirely satisfactory (Crowell, 1987). The inception phase and early history of the Los Angeles basin during Miocene time can be safely described as very complex and influenced by extension, translation, rotation, volcanism, and subsidence in ways not yet completely understood.

The present form and structural relief of the Los Angeles basin was largely established during the phase of accelerated subsidence and deposition that began in Late Miocene time and continued without significant interruption through early Pleistocene time (Yerkes and others, 1965). At the close of Miocene time, the most extensive marine embayment of the Cenozoic occupied the basin area, extending northward perhaps to the foothills of the San Gabriel Mountains and northwestward beyond the present-day Santa Monica Mountains. As much as 4,080 m (13,400 ft) of Upper Miocene strata were deposited in the area of the present-day Puente Hills. Because deposition did not keep pace with subsidence, water depth in the newly-forming central syncline reached about 6,000 feet (1,830 m) late in early Pliocene time (Yerkes and others, 1965).

Even as the central deep formed, marginal areas of the basin began to rise differentially during Pliocene. Increasing tectonic unrest is evident from (1) erosional unconformities, rapid lithofacies changes and local

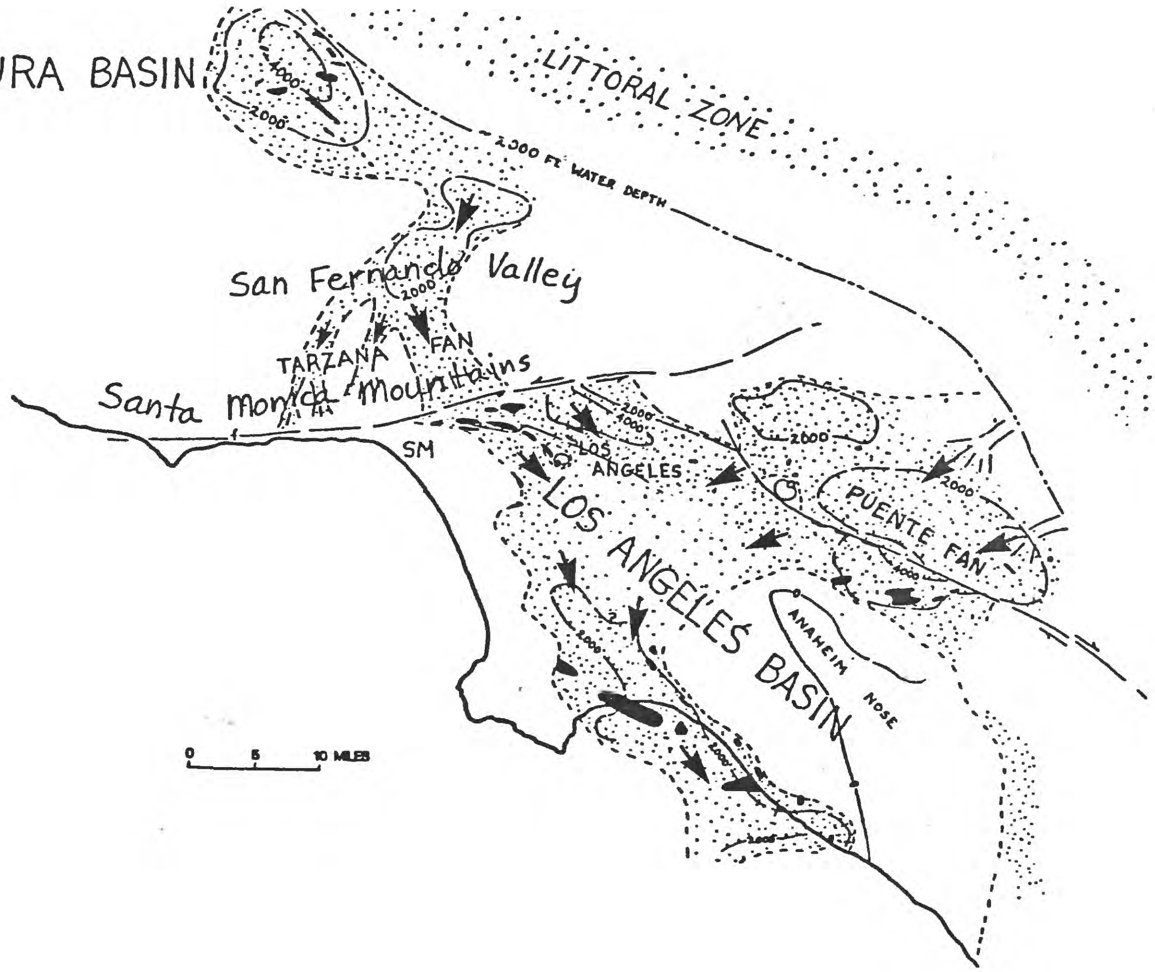

Figure 3. Deep-sea depositional systems of late Middle Miocene age in the Los Angeles region from Wright (1987b) (stippled areas). Arrows show general directions of sediment transport. Isopachs are generalized and oil reservoirs of late Middle Miocene age are shown in black.

faulting, all observed with increasing frequency in successively younger Pliocene sequences around the basin margins, and (2) the development of intermittent isolated structural highs at such locations as the Palos Verdes Hills, Torrance-Wilmington oil fields, Newport-Inglewood zone and Anaheim nose (Yerkes and others, 1965).

The late Pliocene through early Pleistocene history of the Los Angeles basin was characterized by compressive structures, rapid subsidence, high relief and high sedimentation rates that eventually led to the filling of the marine basin in the mid-Pleistocene (Yerkes and others, 1965; Yeats, 1978; Mayer, 1987). Sedimentation rates overtook subsidence rates during the late Pliocene and Pleistocene, as tectonism along the basin margins restricted the area of continuing subsidence and steepened source terranes that fed abundant sediments to the basin (Yerkes and others, 1965). Subsidence and deposition continued to the present time in the central area of the basin where marine strata of Pleistocene age encountered in wells at depths as great as 760 m (2,493 ft) (California Department of Water Resources, 1961; Poland and others, 1956) grade upward into nonmarine Pleistocene and Holocene alluvium. Pliocene and younger strata are more than 5,000 m (16,400 ft) thick in the central syncline (Bostick and others, 1978, fig. 6).

The extensional stress and left-lateral shear that characterized much of Miocene and earliest Pliocene time were replaced in early Pliocene by generally north-south-directed compression that brought new types of displacement to several pre-existing fault systems and generated wholly new structural features. This compression caused (1) north-over-south reverse dip slip on segments of the Malibu Coast-Santa Monica-Raymond Hill-Cucamunga fault system and other generally east-west trending faults, (2) compressional folding and right-lateral faulting along the Newport-Inglewood zone of deformation and other northwest-trending faults, (3) north-over-south oblique-slip displacement and compressional folding along the Whittier fault zone with concomitant uplift of the Puente Hills, and (4) uplift of the Santa Monica and ancestral San Gabriel Mountains of the Transverse Ranges province (Durham and Yerkes, 1964; Yerkes and others, 1965; Yerkes and Campbell, 1971; Yerkes, 1972, Campbell and Yerkes, 1976).

Evidence that north-south compression has continued to present-day is abundant in Los Angeles basin. Latest Pliocene folding that developed 610 m (2,000 ft) of structural relief on the Inglewood anticline has been followed by about 1,220 m (4,000 ft) of right-lateral faulting of the anticline (Wright and others, 1973). Yerkes and others (1965) observed, for example, that (1) strata of late Pleistocene and Pliocene age are steeply tilted and locally overturned just south of the Whittier fault zone, (2) arching and erosion of marine upper Pleistocene and younger rocks has occurred along the Newport-Inglewood zone, and (3) the Palos Verdes Hills have been uplifted about 400 m (1,300 ft) relative to present sea level during middle and late Pleistocene.

Seismicity along the south boundary of the Transverse Ranges indicates that present-day north-south convergence is continuing and is manifested by reverse displacement on east-trending faults and chiefly strike-slip displacement on northwest-southeast-trending faults (Yerkes and others, 1987). The relatively high rate of north-south convergence during the last 3 million years, as earlier proposed by Yeats (1978, 1981), might be due to mid-crustal detachment faulting in which mostly south-vergent thrusts are manifest at shallow depths as folds and reverse faults (Davis, 1987; Davis and Yerkes, 1988).

Structural Setting and Stratigraphy

Yerkes and others (1965) have defined four structural blocks of the Los Angeles basin whose contacts with adjoining blocks are major zones of faulting or flexure in the basement rocks along which vertical and lateral movement took place intermittently during deposition of the superjacent rocks (figs. 1 and 4). These informal subdivisions are convenient to discuss the structure and stratigraphy of the basin and the following summaries are paraphrased almost exclusively from Yerkes and others (1965).

Southwestern Block

This block is bounded on its northeast side by the Newport-Inglewood zone of deformation and extends to the southwest beneath the Pacific Ocean (figs. 1 and 4). Basement rocks of this block, assigned to the pre-Upper Cretaceous Catalina Schist (Schoellhamer and Woodford, 1951), are exposed in the Palos Verdes Hills more than 300 m (1,000 ft) above sea level and are between 1,500 and 4,270 m (5,000 and 14,000 ft) below sea level beneath the coastal plain to the north (fig. 4).

Superjacent rocks are as much as 6,250 m (20,500 ft) thick and are chiefly marine sedimentary strata of Middle Miocene to Holocene age (figs. 5 and 6). Locally they include igneous rocks of middle Miocene age.

The major structural elements of the southwestern block include the northwest-trending, doubly plunging anticline that underlies the Palos Verdes Hills, the steeply southwest-dipping Palos Verdes Hills fault zone on which the hills are upthrown along their northeast margin, and the buried northwest-trending anticlinal arches in the basement surface that underlie the low plain north of the hills (figs. 4 and 7, cross sections AA', BB', and CC').

Northwestern Block

This block is bounded on its southeast side by the Santa Monica-Raymond Hill fault zone, includes the Santa Monica and Verdugo Mountains, and is outside the defined Los Angeles basin province (figs. 1 and 4). Basement rocks of this block, assigned to the Lower Cretaceous and older Santa Monica Slate which, in turn, is intruded by plutonic rocks, are exposed in the eastern Santa Monica Mountains. The plutonic rocks, mostly quartz diorites with local gneissic texture, have been correlated to similar rocks in the San Gabriel Mountains.

The superjacent rocks are about 4,420 m (14,500 ft) thick in the east part of the Santa Monica Mountains and consist of marine clastic sedimentary strata of Late Cretaceous to Pleistocene age and of Middle Miocene volcanic rocks (fig. 8).

The eastern Santa Monica Mountains are formed by a broad west-plunging anticline, which is transected by a northeast-trending branch of the Santa Monica fault zone. The south flank of the anticline is truncated by the Santa Monica fault zone, along which it is upthrown; the north flank dips northward into the San Fernando Valley (figs. 4 and 7, section DD').

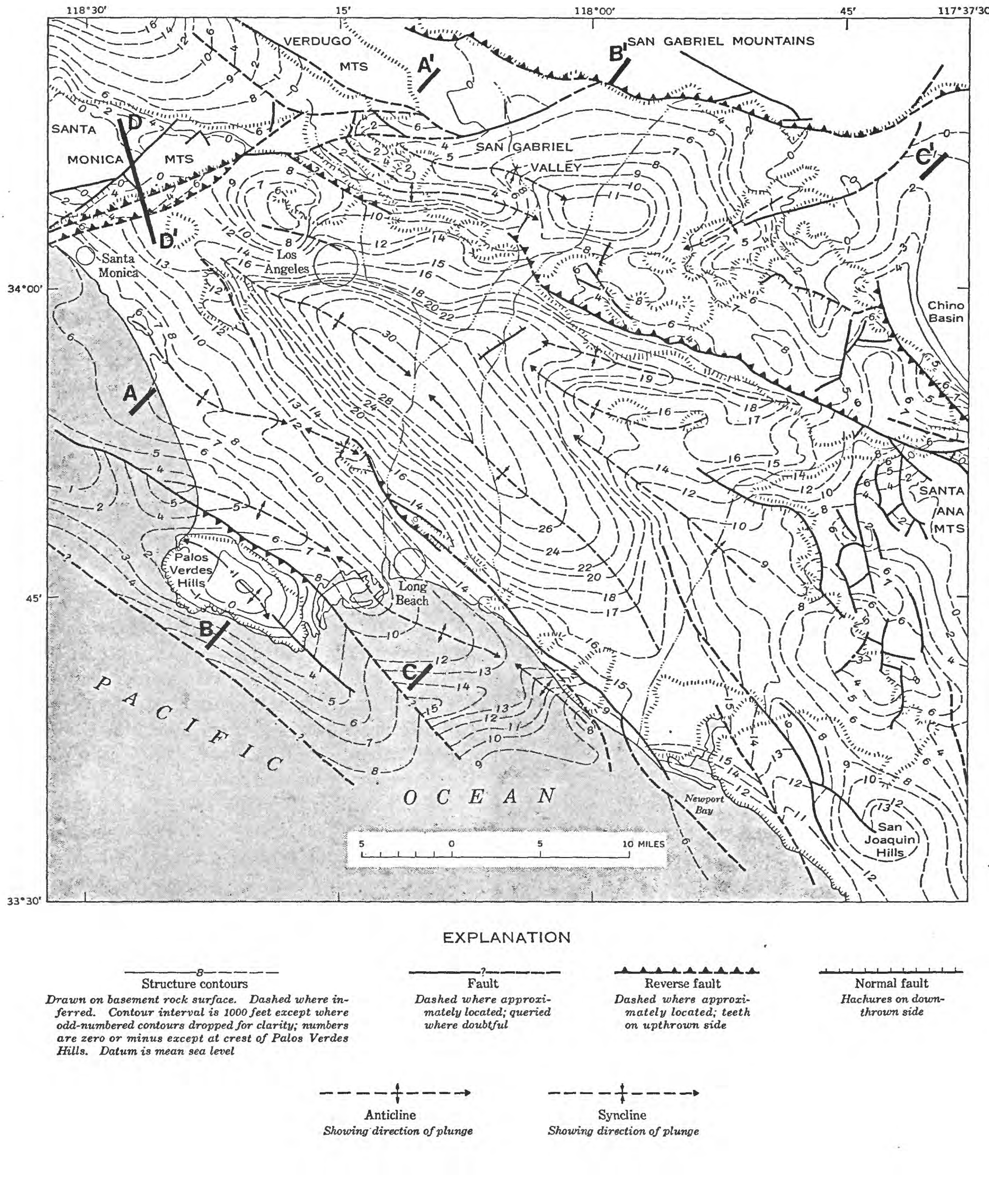

Figure 4. Major structural features and structure contours on the basement surface of the Los Angeles basin (Yerkes and others, 1965). Locations of cross sections AA', BB', CC', and DD' (fig. 7) also are shown.

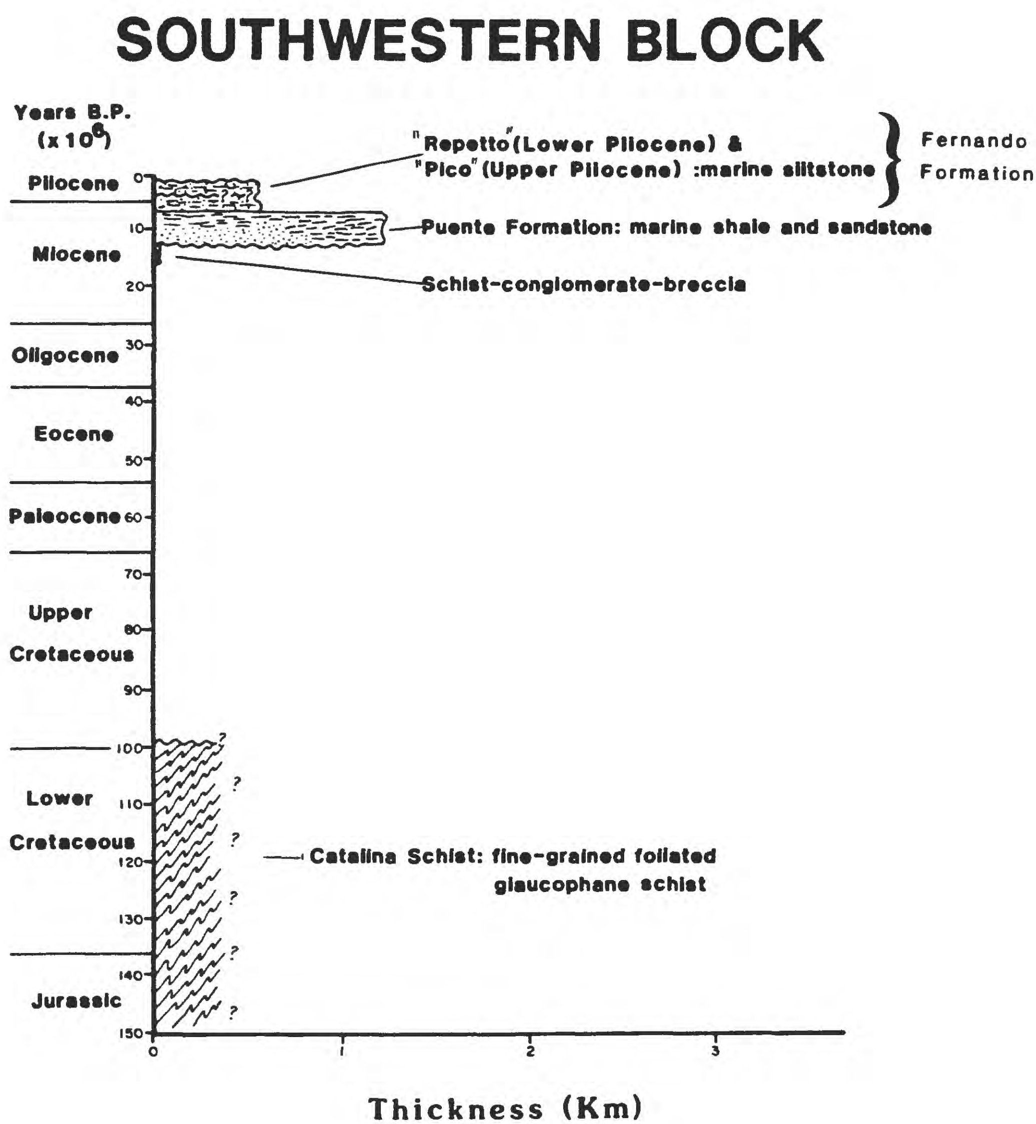

Figure 5. Time-thickness bar diagram for composite stratigraphic column 4 of Yerkes and others (1965) (slightly modified from Mayer, 1987). See figure 1 for location.

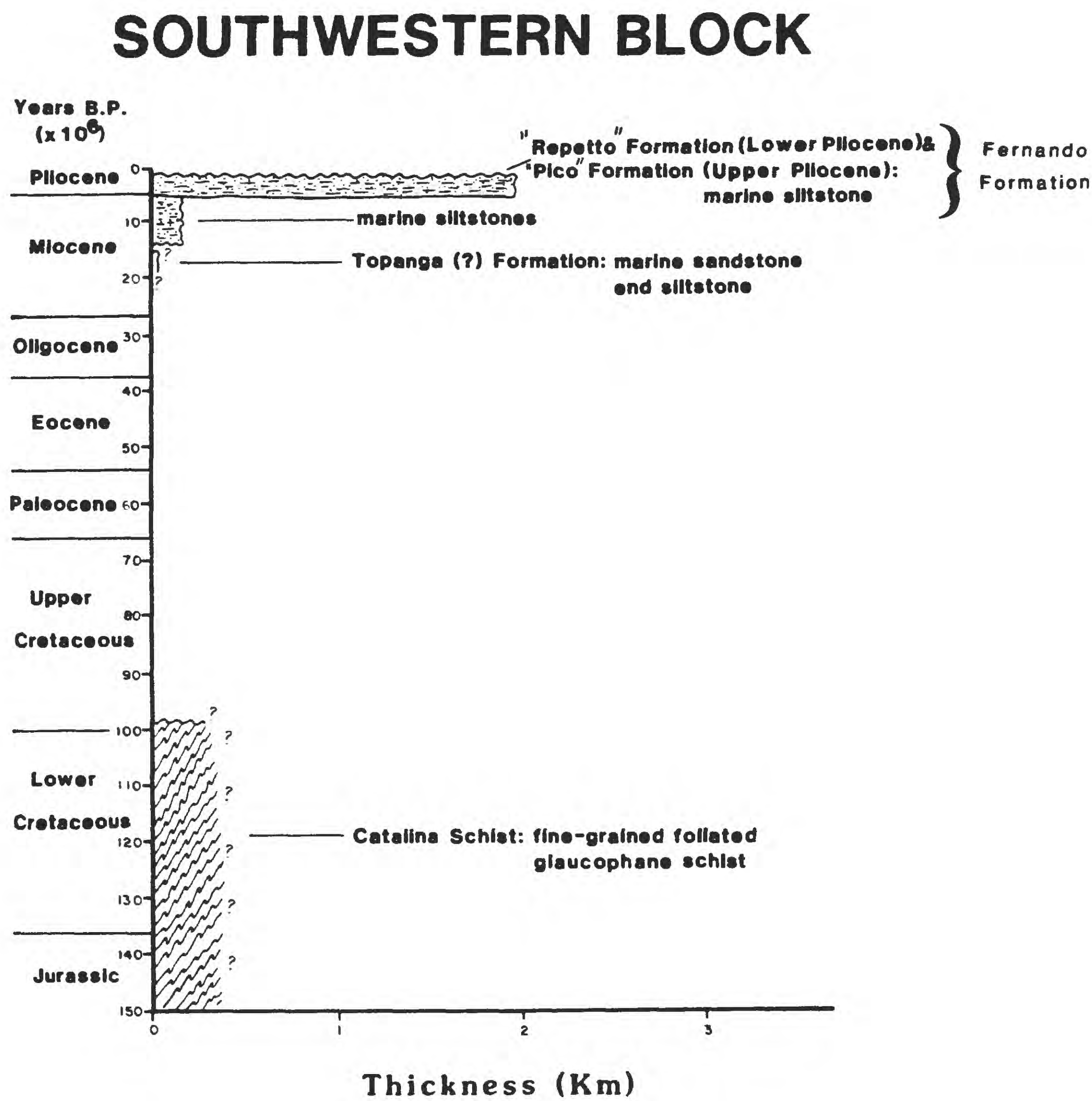

Figure 6. Time-thickness bar diagram for composite stratigraphic column 2 of Yerkes and others (1965) (slightly modified from Mayer, 1987). See figure 1 for location.

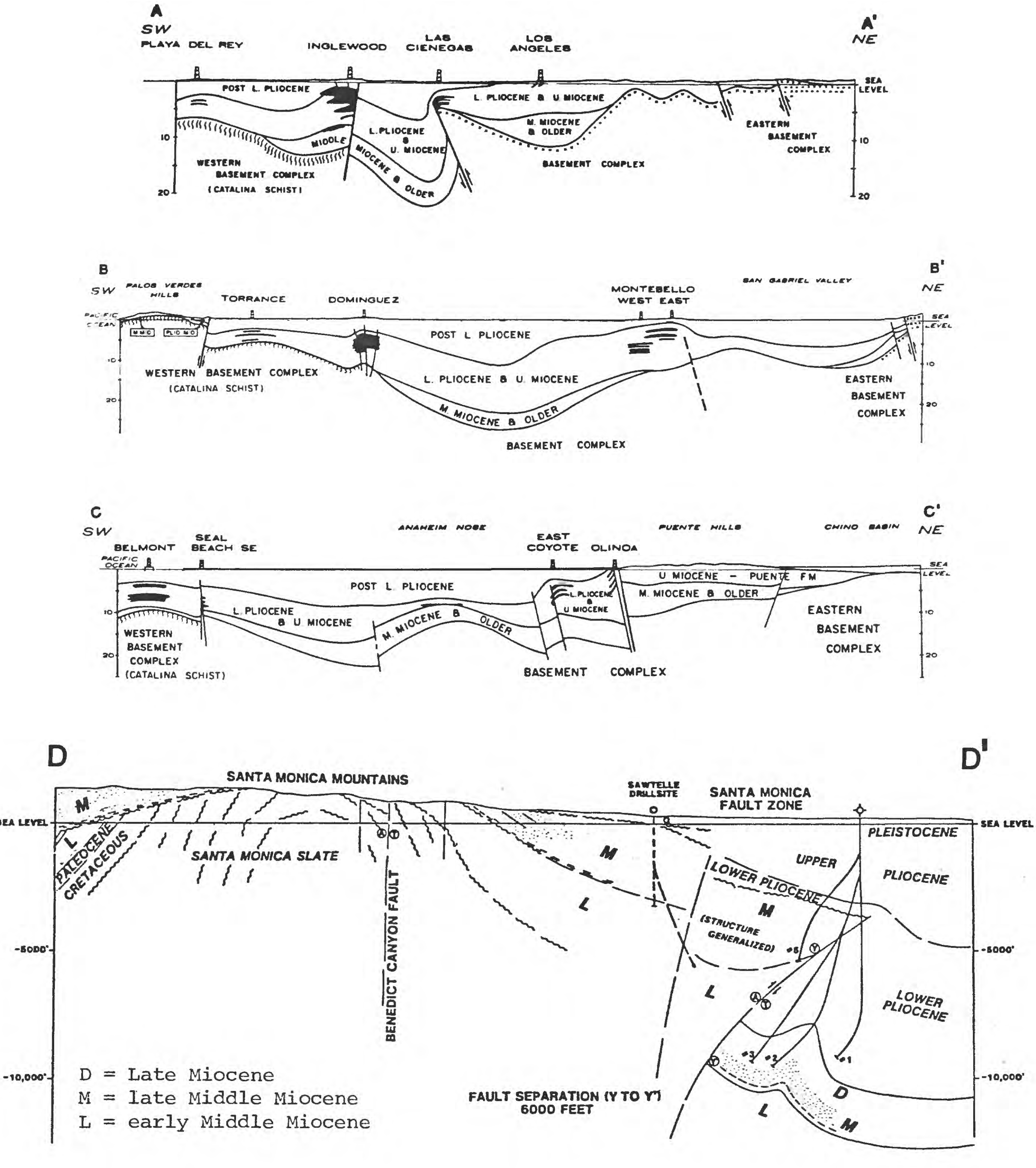

Figure 7. Southwest to northeast-trending generalized cross sections AA', BB', and CC' through Los Angeles basin (Gardett, 1971). Cross section DD' trends northwest to southeast across the Santa Monica fault zone in northwest part of basin (Wright, 1987b). Locations of cross sections are given in figure 4. Selected oil fields are shown on cross sections AA', BB', and CC'.

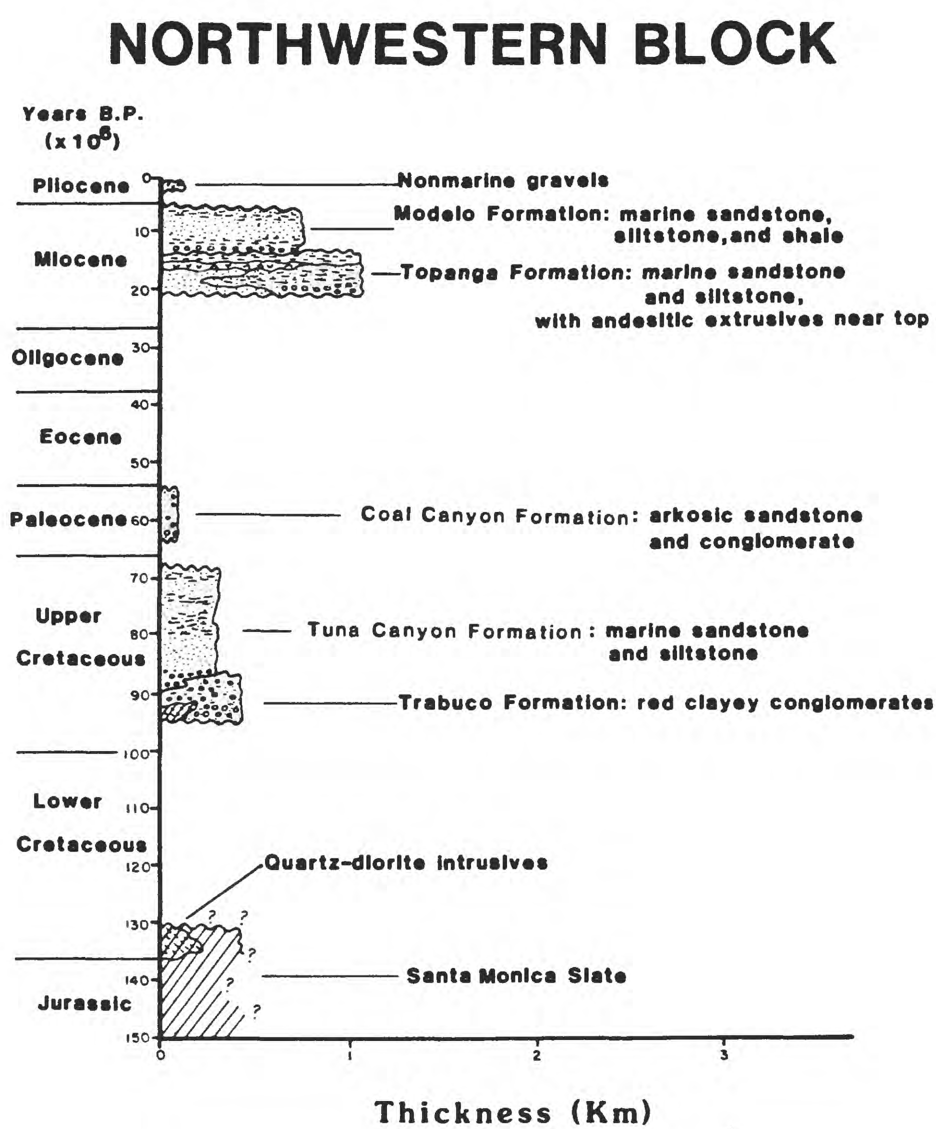

Figure 8. Time-thickness bar diagram for composite stratigraphic column 1 of Yerkes and others (1965) (slightly modified from Mayer, 1987). See figure 1 for location.

Central Block

This wedge-shaped block is bounded by the Newport-Inglewood zone of deformation on the southwest, the Santa Monica fault on the northwest, and the Whittier-Elsinore fault zone on the northeast (figs. 1 and 4). The prominent Santa Ana Mountains rise to an altitude of 1,740 m (5,700 feet) at the east margin, and the low San Joaquin Hills are located at the southeast margin. Basement rocks of this block, including pre-Upper Cretaceous Santiago Peak Volcanics and Bedford Canyon Formation, are exposed in the Santa Ana Mountains, but have not been reached by drill to the northwest.

The superjacent rocks of the central block are best exposed on the west slopes of the Santa Ana Mountains where they attain a maximum thickness of at least 9,750 m (32,000 ft). They consist of marine and nonmarine clastic sedimentary rocks of Late Cretaceous through Pleistocene age and interbedded volcanic rocks of Middle Miocene age. (fig. 9). It is inferred from regional stratigraphic studies that, in the central part of the block, the lower parts of this succession are thinned or missing beneath younger rocks; the Pliocene and Quaternary strata are as much as four times as thick as in the Santa Ana Mountains; and the entire superjacent succession may be as much as 10,670 m (35,000 ft) thick (fig. 10).

The dominant structural feature of the central block is the northwest-trending, doubly plunging synclinal trough underlying its central part (figs. 4 and 7, sections AA', BB', CC'). The basement surface in the axial part of this trough plunges from depths of 3,960 to 4,875 m (13,000 to 16,000 ft) below sea level at its distal ends to depths of at least 9,445 m (31,000 ft) subsea in its central part. The southwest flank of the synclinal trough rises steeply to a subsea depth of about 4,265 m (14,000 ft) along the Newport-Inglewood zone, but its northeast flank rises gently, then abruptly, to merge with a broad, gently sloping shelf that has an average depth of about 4,570 m (15,000 ft) subsea, and that is complicated by several subsidiary folds and faults (figs. 4 and 7).

Northeast Block

This wedge-shaped block is bounded on the north by the Raymond Hill-Cucamonga fault zone and on the southwest by the Whittier-Elsinore fault zones (figs. 1 and 4). Basement rocks of this block, largely pre-Upper Cretaceous granitoid intrusives, are exposed at the north end of the Puente and San Jose Hills.

Superjacent rocks are as much as 7,300 m (24,000 ft) thick, range in age from Paleocene to Quaternary, and consist chiefly of fine- to coarse-grained marine clastic rocks (fig. 11). In the eastern part of the block, this marine section locally includes more than 1,200 m (4,000 ft) of Middle Miocene volcanic rocks. In the central Puente Hills, the greatest known thickness of Upper Miocene marine rocks in the basin occur--about 4,100 m (13,400 ft). In the San Gabriel Valley, marine(?) and nonmarine Quaternary rocks are as much as 1,800 m (6,000 ft) thick.

The configuration of the basement surface is reflected in the topography of the block. Beneath the San Gabriel Valley, a closed elliptical depression

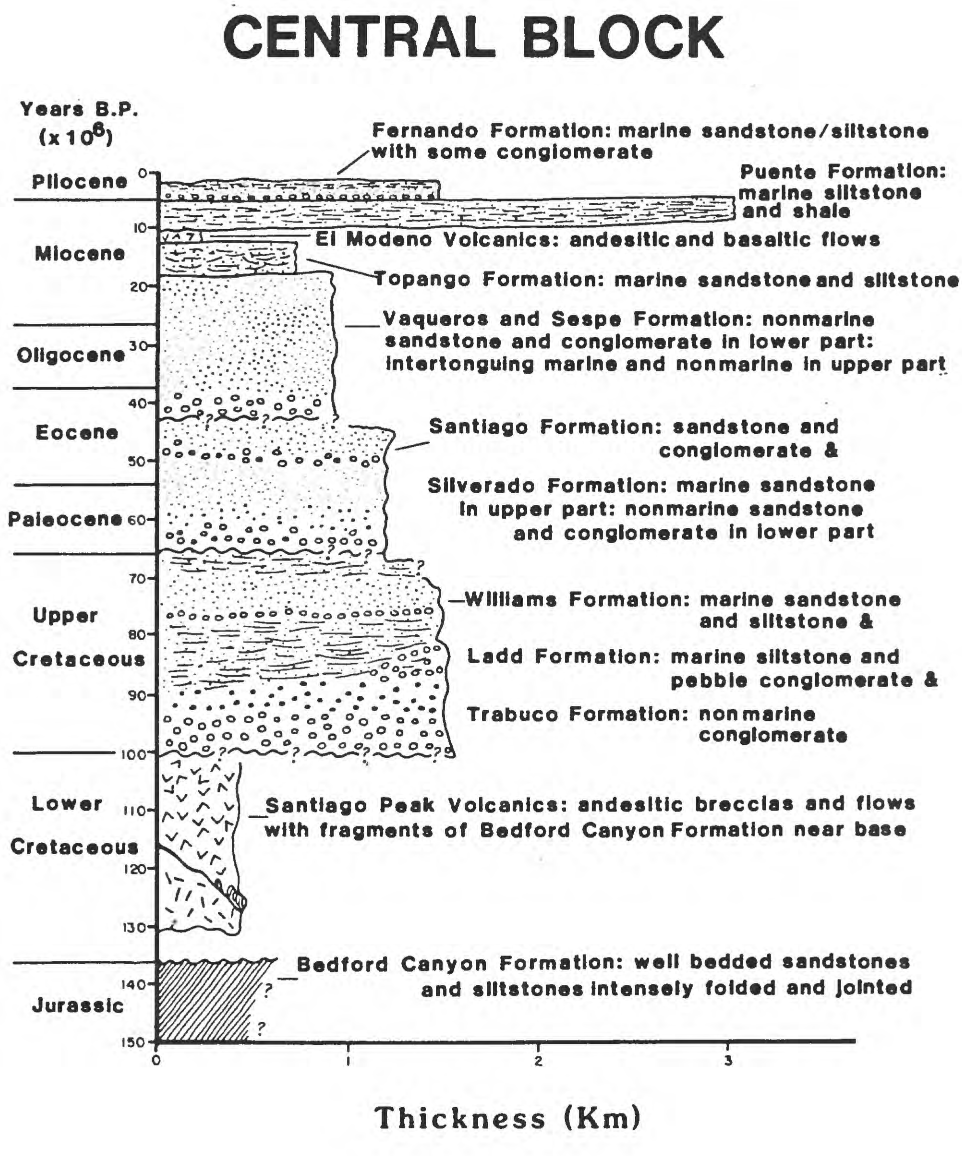

Figure 9. Time-thickness bar diagram for composite stratigraphic column 11 of Yerkes and others (1965) (after Mayer, 1987). See figure 1 for location.

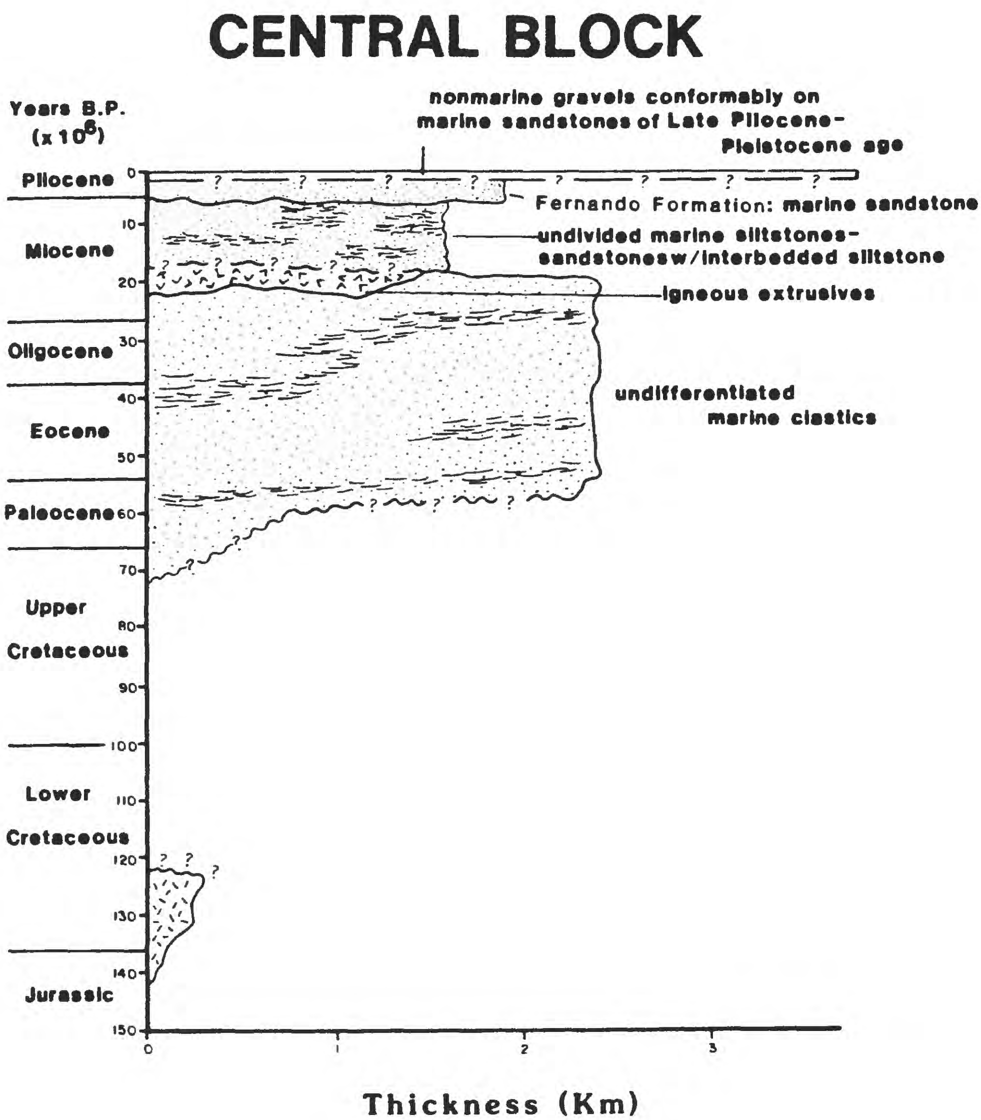

Figure 10. Time-thickness bar diagram for composite stratigraphic column 6 of Yerkes and others (1965) (slightly modified from Mayer, 1987). See figure 1 for location.

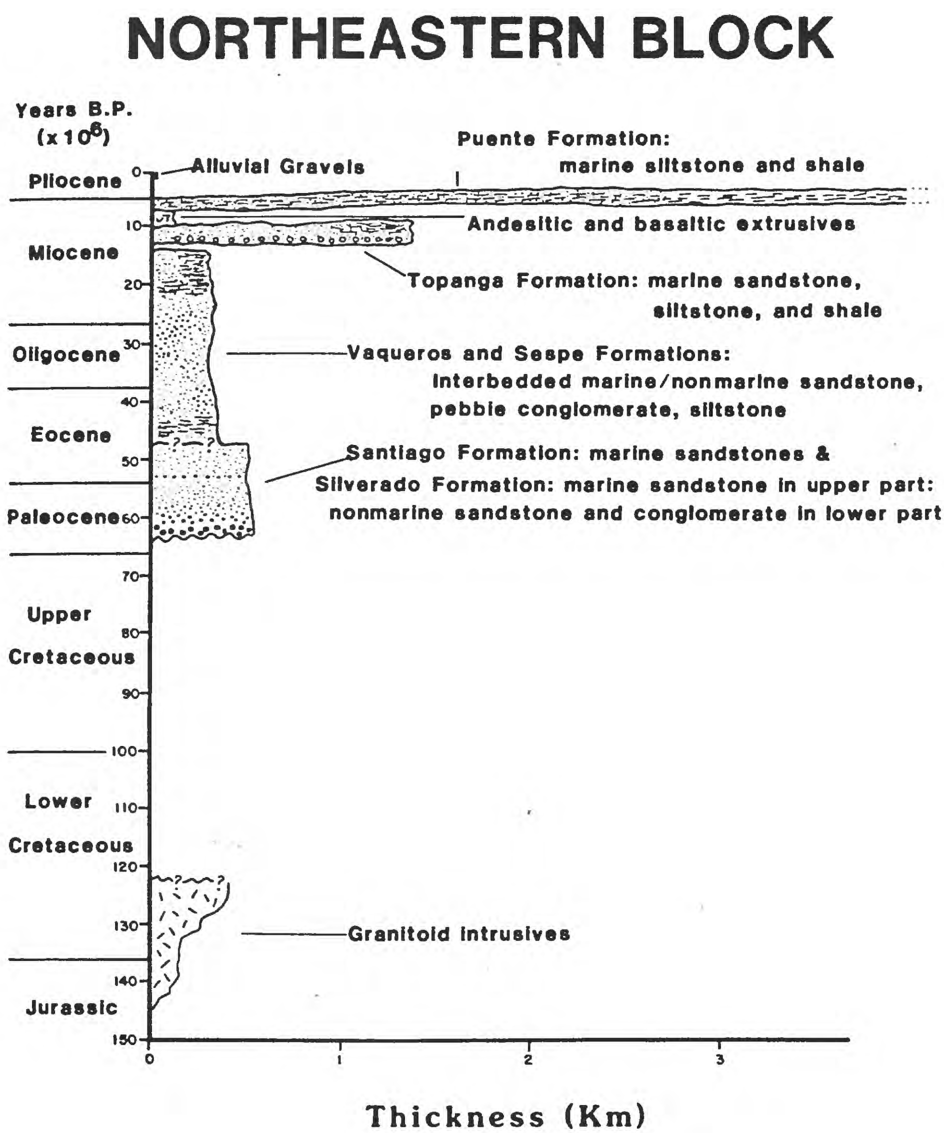

Figure 11. Time-thickness bar diagram for composite stratigraphic column 14 of Yerkes and others (1965) (after Mayer, 1987). See figure 1 for location.

on the basement surface reaches a subsea depth of about 12,000 feet (fig. 4). The low hills southwest of the valley are underlain by the east-plunging Elysian Park anticline, which rises to subsea depths of 305 to 1,220 m (1,000 to 4,000 ft) (figs. 1 and 4). Beneath the Puente Hills southeast of the San Gabriel Valley is a roughly triangular area that has a general southwest slope from sea level at the north to 2,440 m (8,000 ft) subsea at the south; this area is complicated by subsidiary ridges, depressions, and faults. The San Jose Hills east of the valley are underlain by an elongated southwest-plunging anticline. The Chino basin is a narrow south-plunging depression at subsea depths of 610 to 2,440 m (2,000 to 8,000 ft). The basement surface of the block is cut by northwest- to northeast-trending faults that break through the superjacent rocks to the surface.

Depositional Systems of Reservoir Rocks

Middle Miocene through middle Pleistocene marine sediments were transported and deposited in deep-water environments largely by turbidity currents channeled down submarine canyons located on the north, northeast and east margins of Los Angeles basin (Sullwold, 1960; Durham and Yerkes, 1964; Yerkes and others, 1965; Conrey, 1967; Gourley, 1975; Yerkes, 1972; Schoellhamer and others, 1981; Redin, 1984; Wright, 1987b). During Middle Miocene time, major submarine fan systems prograded (1) into the northwest part of the basin from north of the present location of the Santa Monica Mountains (the Tarzana fan of Sullwold, 1960) and (2) southwestward across the present-day eastern Puente Hills (the Puente fan of Gourley, 1975) (fig. 3).

Increasingly distal deposits of the Tarzana and Puente fan systems apparently merged west of the Anaheim nose, lapped against and partly over the structurally high northern part of the southwest block approximately along the Newport-Inglewood zone, and turned southeastward to fill a trough between the present-day Palos Verdes Hills fault and the Newport-Inglewood zone where thick sandstone sequences form reservoirs in the Wilmington and offshore Huntington Beach oil fields (Wright, 1987b) (figs. 1 and 3).

Deposition in Los Angeles basin from the Tarzana fan system ended before Late Miocene time (about 12 Ma) but the axis of the Puente submarine fan system shifted progressively westward during the Upper Miocene, according to Wright (1987b). The gradual development of the Whittier fault zone, the infilling of the depression in the San Gabriel Valley so sediments could be carried southward into the Los Angeles basin, and tectonic uplift of source areas to the north during Upper Miocene time presumably influenced the westward shift of the Puente fan system, although the details remain obscure. Coarse-grained deposits began to reach southward into the Los Angeles basin from the San Gabriel Valley in the vicinity of the Whittier Narrows and Whittier Hills (fig. 1) via a submarine canyon-channel complex during the early Late Miocene according to Gourley (1975). These deposits probably are part of a lower Pliocene submarine fan complex, termed the Montebello-Whittier fan complex, of Conrey (1967) or the westward migrated Puente fan of Wright (1987b) that persisted in the vicinity of Whittier Narrows as the largest single source of sediments to the basin until shoaling occurred during mid-Pleistocene (Wright, 1987b) (fig. 12). Additional sediments were intermittently furnished to the basin during late Neogene time from the present sites of the Santa Monica and Santa Ana Mountains, Chino and Puente Hills, and Palos Verdes Hills (Yerkes and others, 1965; Conrey, 1967).

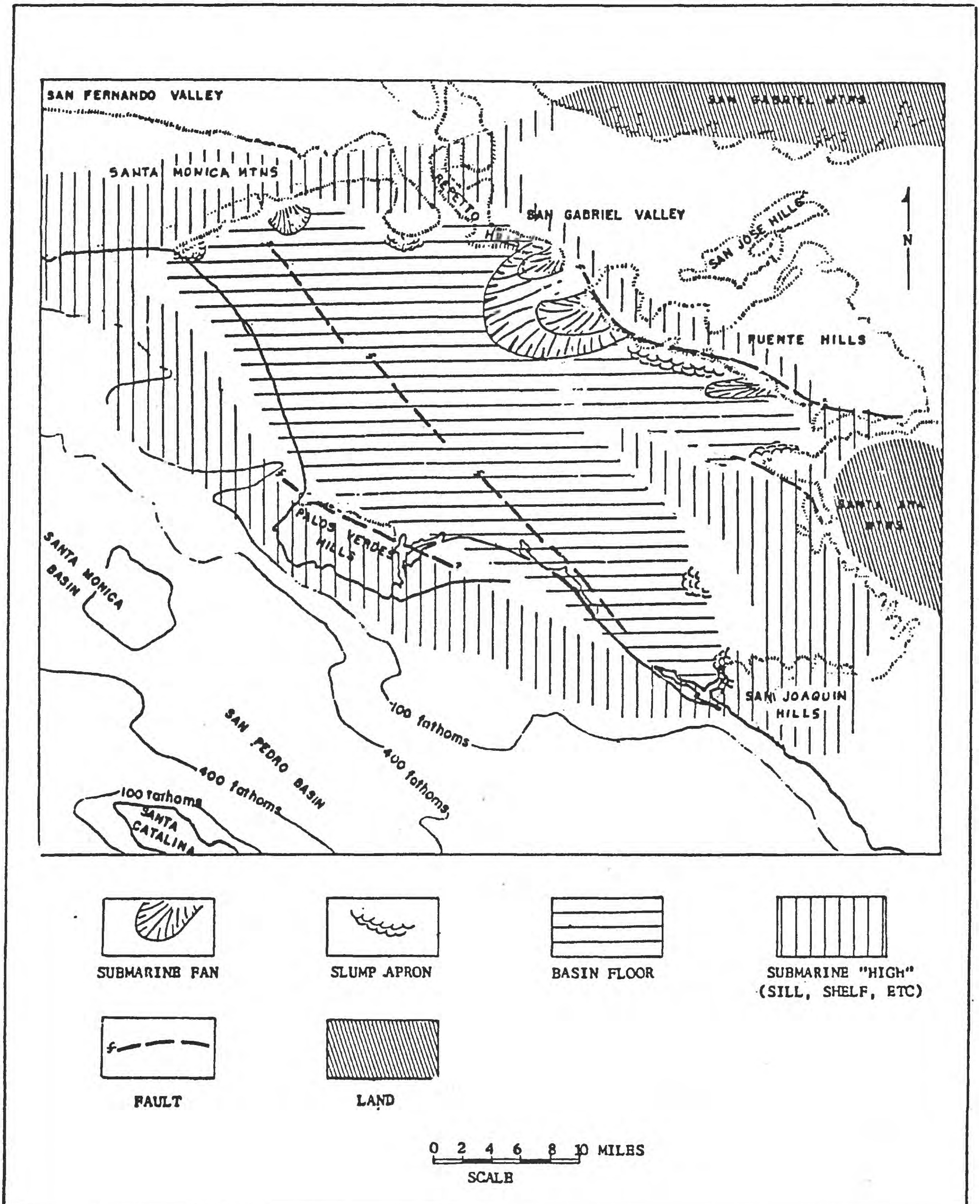

Figure 12. Paleophysiographic map of Los Angeles basin during early Pliocene time shown with minor revision from Wright (1987b) who modified original of Conrey (1967).

Depositional patterns in Los Angeles basin during Neogene were often controlled by vertical tectonism within and surrounding the basin. Thinning of lower Pliocene rocks over the Wilmington-Torrance anticlinal trend and the Coyote uplift (fig. 1) and frequent unconformities in marginal areas indicate both structural growth and occasional emergence of different parts of the basin during late Noegene (Yerkes and others, 1965). Deposition in the relatively confined central syncline was strongly controlled by paleobathymetry (Redin, 1984; Wright, 1987b) where at least one described turbidite sequence is reported to vary from classical models based on unrestricted deposition (Schweller and others, 1987). Debris, grain and fluidized sediment flows are also reported as sediment transport mechanisms (Redin, 1984) and "slump aprons" are described at several places by Conrey (1967) (fig. 12). However, most oil reservoir rocks are believed to be parts of the proximal to distal facies of submarine canyon-fan depositional systems (Redin, 1984).

Subsidence History

The most comprehensive subsidence analysis of Los Angeles basin available at this writing is provided by Mayer (1987, p. 314-315) who relied primarily on data from Yerkes and others (1965): "Prior to about 28 my B.P.,...subsidence of the basin floor was slow, with little net tectonic subsidence. After 28 my B.P., the basin floor began to subside more rapidly, but sedimentation kept pace, and therefore, a deep-water basin did not develop. Sedimentation increased its rate slightly during the time of Topanga deposition in the interval from about 21 to 12 my B.P., but the rate of basin-floor subsidence increased by a larger amount, so that a deeper water-filled basin developed. Between 21 and 10 my B.P., the basin floor subsided at a very high rate. Relatively low sedimentation rates during deposition of the Monterey and Capistrano formations (ca. 12-3 my B.P.), combined with a high subsidence rate, resulted in a very deep water-filled basin."

"The basin continued to deepen until sometime during the early Pliocene, perhaps 3 my B.P. The subsidence history from the early Pliocene to the Pleistocene was characterized by continued subsidence of the basin floor, but also by a rapid pulse of sedimentation that filled the basin at a rate of about 1.5 km/my. The continued subsidence of the basin floor was entirely due to sediment loading, unlike the San Joaquin Hills area, where uplift began about 3 my B.P. (Ingle, 1980). The trend of the complete tectonic-subsidence curve after 3 my B.P. in the deep part of the central block indicates that all tectonic subsidence had ceased."

A geohistory diagram for the central part of Los Angeles basin (Mayer, 1987) and a "time-depth-thickness" diagram (Yerkes and others, 1965) are given in figure 13. See Yeats (1978) for a discussion of the possible causes of this subsidence and Wright (1987b) for a narrative description of the subsidence and sediment filling of Los Angeles basin.

Subsurface Temperatures and Pore-Fluid Pressures

Reliable published temperature data for the Los Angeles basin are very limited (Carlson, 1930; French, 1940; Doyle, 1958; Sass and Munroe, 1974; Mayuga, 1970; Bostick and others, 1978; McCulloh and others, 1978; Walker and others, 1983). Present-day temperature gradients are reported to range from about 30^{o} C/km (1.65^{o}F/100 ft) in the central syncline (McCulloh and others, 1978) to as high as about 60^{o} C/km (3.29^{o}F/100 ft) in the onshore Wilmington

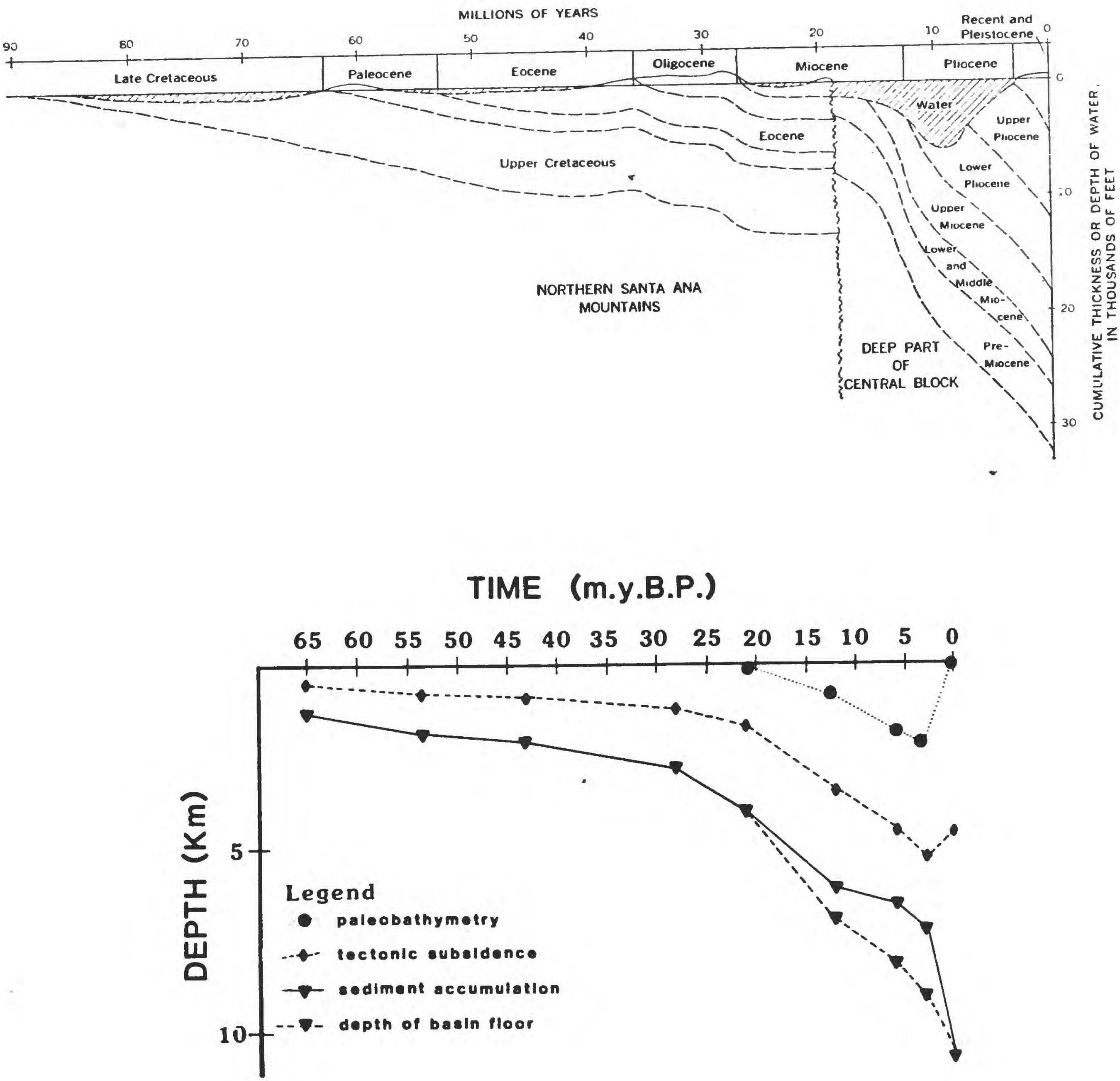

Figure 13. Top: diagram of relationship between thickness, water depth, and time for two parts of the central block of the Los Angeles basin during deposition of superjacent rocks (Yerkes and others, 1965). Bottom: geohistory diagram illustrating subsidence history of the central block of the Los Angeles basin (Mayer, 1987).

oil field (Mayuga, 1970) with a basin average of about 39^o C/km (2.14^{o}F/100 ft) (Phillippi, 1965) (fig. 14). Generally, higher subsurface temperatures and temperature gradients occur along the southwestern margin of the Los Angeles basin than in the central syncline (where they are lowest) and northeast area of the basin. Present-day temperatures in the basin may not everywhere be historical maximum values due, for example, to changes in heat flux from below, uplift and removal of overburden or changes in fluid transport through the sedimentary section. However, in many areas in and around the central syncline present-day temperatures are believed to be post-burial maximums within the upper Miocene and younger section (McCulloh and others, 1978; Naeser and others, 1987).

Further work is needed to determine the heat-flow variations within the Los Angeles province and to examine the thermal history recorded in pre- and post-upper Miocene rocks. For example, it is not known why higher temperature gradients occur along the southwest margin of the basin, if a transient thermal event was associated with the middle Miocene volcanism, and if, as suggested by McCulloh and others (1978), subsurface isotherms have recovered from being depressed downward by the rapid basin subsidence and in-filling during Neogene. Lastly, the published thermal gradient map for the Los Angeles basin is of questionable quality, suggesting further work is needed (American Association of Petroleum Geologists, 1975).

Pore-fluid pressure gradients encountered during drilling of most Los Angeles basin wells range from 0.0638 to 0.0812 kPa (0.44 to 0.56 lbf/in^2), well within the range generally considered "normal hydrostatic" (McCulloh and others, 1978).

Petroleum Source Rocks, Maturation and Migration

The presence of abundant, rich source rocks in the Los Angeles province is indisputable: More reservoired oil-per-unit basin volume has been discovered in Los Angeles basin than in any other thoroughly explored basin in the world (McFarland and Greutert, 1971; Perrodon, 1972). The hydrocarbon richness of the basin is due to a very favorable (and rare) sequence of events. Abundant oil-prone organic matter was deposited in pelitic sediments in generally low-oxygen environments, often with interbedded or interfingering turbidite sands (Barbat, 1958). Relatively rapid burial, preserving organic matter, and maturation and expulsion of oil coincided with deformation and trap formation along major structural trends (Barbat, 1958; Yerkes and others, 1965). Lastly, petroleum development of the basin occurred before ongoing processes of uplift and erosion could destroy a significant proportion of most early formed reservoirs (Wright, 1987b; Yeats, 1987). Estimates of the percentage of generated oil that has been trapped in reservoirs range from an astounding 10 to 20 percent (McDowell, 1975; Jones, 1981), far more than has been estimated for other U.S. basins.

The "nodular shale", the late middle Miocene basal unit of the Modelo Formation in the northwestern part of Los Angeles basin, generally is accepted today as a major source rock in that area (Wissler, 1943; Walker and others, 1983). An early remarkable study offered convincing evidence, based on compositional similarities and variations of oils in the "nodular shale" and reservoirs, that the "nodular shale" was the source rock for oil reservoired in underlying schist conglomerate and overlying marine sandstone in the Playa del

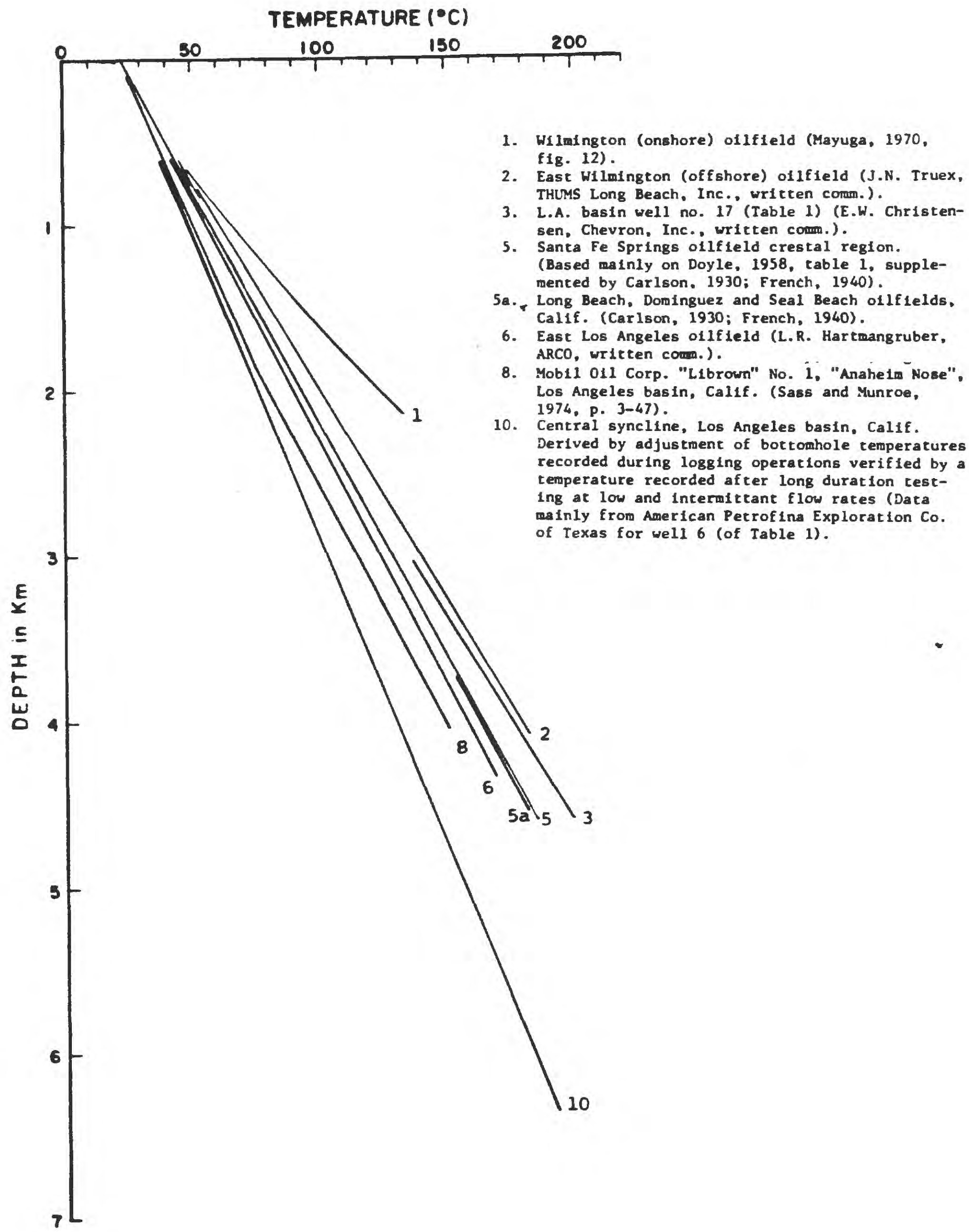

Figure 14. Subsurface temperature profiles for eight well sites in the central Los Angeles basin (adapted from McCulloh and others, 1978). Locations of profiles described in inset.

Rey oil field (Hoots and others, 1935). The nodular shale is a finely laminated, bituminous, marine shale that contains abundant phosphatic nodules, foraminiferal tests, fish scales, and fine particulate organic matter derived from algal sources (Walker and others, 1983). Some thin interbeds of dolomite, chert, and bentonite (volcanic ash) are found in this shale unit which presumably was deposited on deeply submerged offshore ridges and slopes largely protected from terrigenous sediments (Wright, 1987c). In seven core samples studied by Walker and others (1983), total organic carbon ranged from 2.2 to 9.4 weight percent, and over 90 percent of the organic matter was amorphous degraded algal material.

Probable stratigraphic and time equivalents of the "nodular shale" west of the Newport-Inglewood zone of deformation include the Altamira Shale Member of the Monterey Shale exposed in the Palos Verdes Hills (Woodring and others, 1946; Conrad and Ehlig, 1983) and the "black shale member" of the "237 zone", which produces oil from fractures in the Long Beach unit of the Wilmington oil field (Truex, 1972). The La Vida Member of the Puente Formation in the northeast Los Angeles basin, composed principally of terrigenous debris, is the approximate stratigraphic and time equivalent of the "nodular shale" (Schoellhamer and others, 1981; Wright, 1987c).

Work by Philippi (1965, 1974, 1975) Bostick and others (1978) and Price (1983), and observations by Cordell (1972, 1974) and Jones (1981), clearly indicate that upper Miocene and Pliocene sediments also contain significant organic matter, though dilution by terrigenous debris generally increases stratigraphically upward beginning in the Pliocene section. That upper Miocene and(or) lower Pliocene source rocks, located in deeper parts of the basin, are responsible for reservoired oil, is agreed by these investigators, although they differ about maturation temperature, migration mechanism and migration pathways. Pertinent to these arguments is the fact that more than 99 percent of the discovered, producible oil occurs in upper Miocene and lower Pliocene rocks in reservoirs at depths less than about 2,000 m (6,500 ft) (Barbat, 1958; Taylor, 1976). Upper Pliocene reservoirs contain only about 0.1 percent of the discovered oil, and only in association with major faulting (Jones, 1981). Middle Miocene reservoir rocks accounted for only 0.25 percent of the basin's cumulative production through 1974 (Taylor, 1976).

In a study of crude oils from the Dominguez, Huntington Beach and Wilmington oil fields and the "indigenous" organic matter in upper Miocene through Holocene shale from only two drillholes in Los Angeles basin, Philippi (1965, 1974) concluded that (1) the bulk of the oil generation takes place below 8,000 ft (2,438 m) at temperatures above 115° C (239° F), (2) only in upper Miocene D and E shales which have been buried at least 10,500 ft (3,200 m) do the naphthene index and the normal paraffin odd/even ratio values simultaneously equal the values of the crude-oil hydrocarbons, and (3) vertical migration from upper Miocene D and E shales must have been extremely common and occurred through faults and fractures. Note that Miocene D and E shales are approximately equivalent to the "nodular shale", and that the temperature at 10,500 ft (3,200 m) is about 145° C (293° F).

Cordell (1972, 1974) interprets Philippi's (1965) data differently to conclude that younger shales at shallower depths have sourced petroleum now in reservoirs in the Los Angeles basin. Jones (1981) used early descriptions of the "nodular shale" and the Playa del Rey field (Hoots and others, 1935), mass-balance calculations and the restriction of practically all discovered oil reservoirs to upper Miocene and lower Pliocene rocks to argue that most oil migrated in a continuous phase from interlayered thermally mature source rocks deeper in the basin. He observed that the abrupt cessation of reservoired oil near the top of the lower Pliocene section correlates well with the top of peak (hydrocarbon) generation in equivalent stratigraphic units in the basin center. Jones (1981) and Cordell (1972, 1974) concluded that vertical migration across stratigraphic boundaries over thousands of feet, as proposed by Philippi (1965, 1974), is not likely in the Los Angeles basin, even with the presence of fractures and faults.

Price (1983) and Price and Backer (1985) argue that there is no tendency towards commencement of main-stage hydrocarbon generation in Los Angeles basin shales at present-day burial temperatures up to 170° C (338° F). This conclusion is based primarily on pyrolysis (and solvent extraction) of samples from the Wilmington oil field and other unspecified areas. Most other investigators and relationships between source rocks, reservoirs and burial temperatures west of the Newport Inglewood zone of deformation (e.g., Hoots and others, 1935; Wissler, 1943; Truex, 1972; Walker and others, 1983) suggest maturation and migration have occurred at lower temperatures. The presence of significant amounts of sulfurs in lower gravity crude oil produced from this part of Los Angeles basin (Hoots and others, 1935; Winterburn, 1943) suggest that generation of heavy oil from high-sulfur kerogens at lower thermal exposure as concluded by Orr (1986) in a study of Santa Maria basin, California, also may have occurred in parts of Los Angeles basin. Price (personal communication, 1988) acknowledges the role of sulfur in lowering maturation temperatures, and is conducting experiments to evaluate its effect. It is clear that public-domain studies of the organic geochemistry, and migration of petroleum in the Los Angeles basin remain incomplete.

One further aspect of the organic matter studies of Los Angeles basin is worthy of mention. Careful study of first-cycle vitrinite in samples of the highly organic carbon-rich "nodular shale" has shown that organic matter dominated by amorphous algal material matures at a significantly faster rate, and, therefore, at lower time-temperature index (TTI) values than structured organic debris (Walker and others, 1983). Vitrinite reflectance also is "suppressed" in sandstone, siltstone, and shale from widely distributed locations in Los Angeles basin (Bostick and others, 1978; Price and Barker, 1985) (fig. 15). Samples analyzed in these studies had significant to dominant concentrations of exinite macerals and total organic carbon contents of 1 to 9 weight percent.

Price and Barker (1985) concluded that "suppression" of vitrinite reflectance is independent of total organic carbon content, but occurs in rocks with significant to dominant concentrations of exinite or hydrogen-rich macerals. McCulloh and Fan (1985) stated that hydrocarbon-rich environments retard vitrinite reflectance. Based on these studies, use of vitrinite reflectance alone as an index of maturation in the Los Angeles basin is inappropriate when compared with reflectance data from basins whose source rocks do not contain hydrogen-rich macerals (Price and Barker, 1985). Walker and others (1983) concluded that a combination of optical and chemical analysis, such as thermal alteration index (TAI), carbon preference index (CPI), and the ratio of extractable heavy hydrocarbons to organic carbon is a more definitive indicator of thermal maturity.

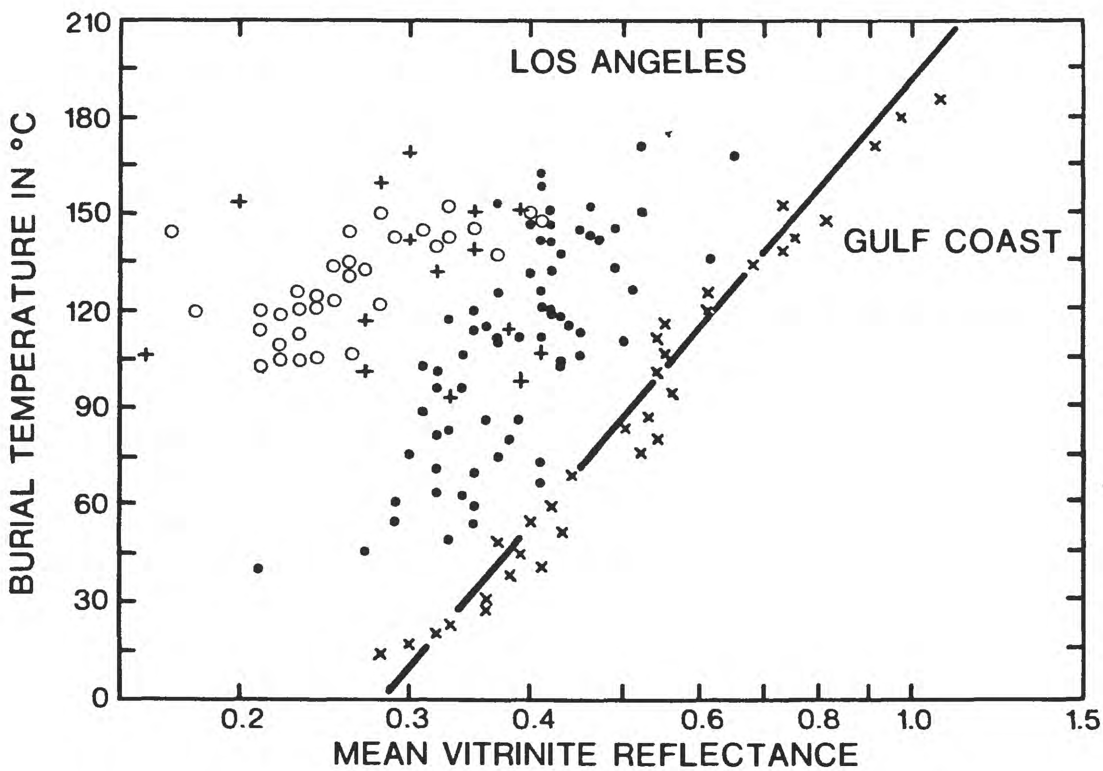

Figure 15. Comparison of observed mean vitrinite reflectance values versus burial temperature for samples from (●) central syncline, northeast flank, Anaheim nose and Santa Fe Springs oil field (Bostich and others, 1978, (+) Wilmington oil field (Price and Barker, 1985), (o) "nodular shale" in northwest Los Angeles basin (Walker and others, 1978), and (x) offshore Gulf Coast (Price and Barker, 1985) (modified from Price and Barker, 1985). Line is "best fit" by regression analysis to Gulf Coast data. Adapted from Price and Barker (1985).

Diagenesis of Petroleum Reservoir Rocks

Sandstones of the Los Angeles basin generally are mineralogically immature and may contain significant amounts of feldspar, mica, igneous and metamorphic rock fragments, and(or) argillaceous matrix, making them more susceptible to diagenetic alteration than, for example, the more mineralogically mature sandstones of the Gulf Coast. Diagenesis of mineralogically immature sandstones in California Cenozoic basins has received increased attention in recent years, presumably because exploration for subtle and deeper reservoirs, as well as improved recovery efficiency from existing reservoirs, requires better understanding and prediction of reservoir porosity, permeability, and timing of hydrocarbon migration. The long-standing tradition of cutting and archiving conventional cores has been invaluable to these more recent investigations. See Beyer and Bartow (1988) for a description of diagenetic studies of immature sandstones in the San Joaquin basin that has some applicability to Los Angeles basin.

McCulloh and others (1978) described the first occurrence with depth of the permeability- and porosity-reducing calcium zeolite mineral laumontite in 15 wells in the Los Angeles basin and constructed the distribution of its first occurrence with depth (figs. 16 and 17, table 1). They concluded that the stratigraphic and structural discordance of their observed laumontite diagenetic "front" was caused by the dependence of laumontite formation on both pore-fluid pressure and temperature, relationships they subsequently refined (McCulloh and Stewart, 1979).

A diagenetic "front" that separates extensive laumonitization and albitization above from widespread carbonate cementation below has been described at a depth of about 2,580 m (8,465 ft) in the Santa Fe Springs oil field (Coffman, 1987). Carbonate cementation is believed to have preceded laumonitization and insulated the sandstones from further diagenesis. Within the underlying carbonate zone, secondary porosity is extensive in some horizons and within the overlying laumontite zone some porosity occurs, apparently the result of selective dissolution. This suggests laumontization is not necessarily economic basement in petroleum exploration.

Porosity of Petroleum Reservoir Rocks

Porosity and permeability of sandstones are governed by compactional and diagenetic processes. These processes are controlled by such factors as the original detrital mineralogy, texture and organic content of the sandstone, its depositional environment and rate of burial, and post-burial histories of temperature, pore-fluid chemistry, pore-fluid pressure, and confining stresses (McCulloh, 1967b).

Published studies of sandstone porosity in the Los Angeles basin include McCulloh (1960; 1967a), Donovan (1963), McCulloh and others (1967, 1968, 1978), Beyer (1983) and Dixon and Kirkland (1985). These studies are based on total porosity measurements of thousands of samples of conventional cores taken from many wells and several borehole gravity surveys in the Santa Fe Springs and Wilmington oil fields. Several conclusions about the systematics of sandstone porosity in Los Angeles basin can be reached from these studies. The rate of decrease of porosity with increasing depth, the porosity-depth gradient, generally is greater for sandstones of the Los

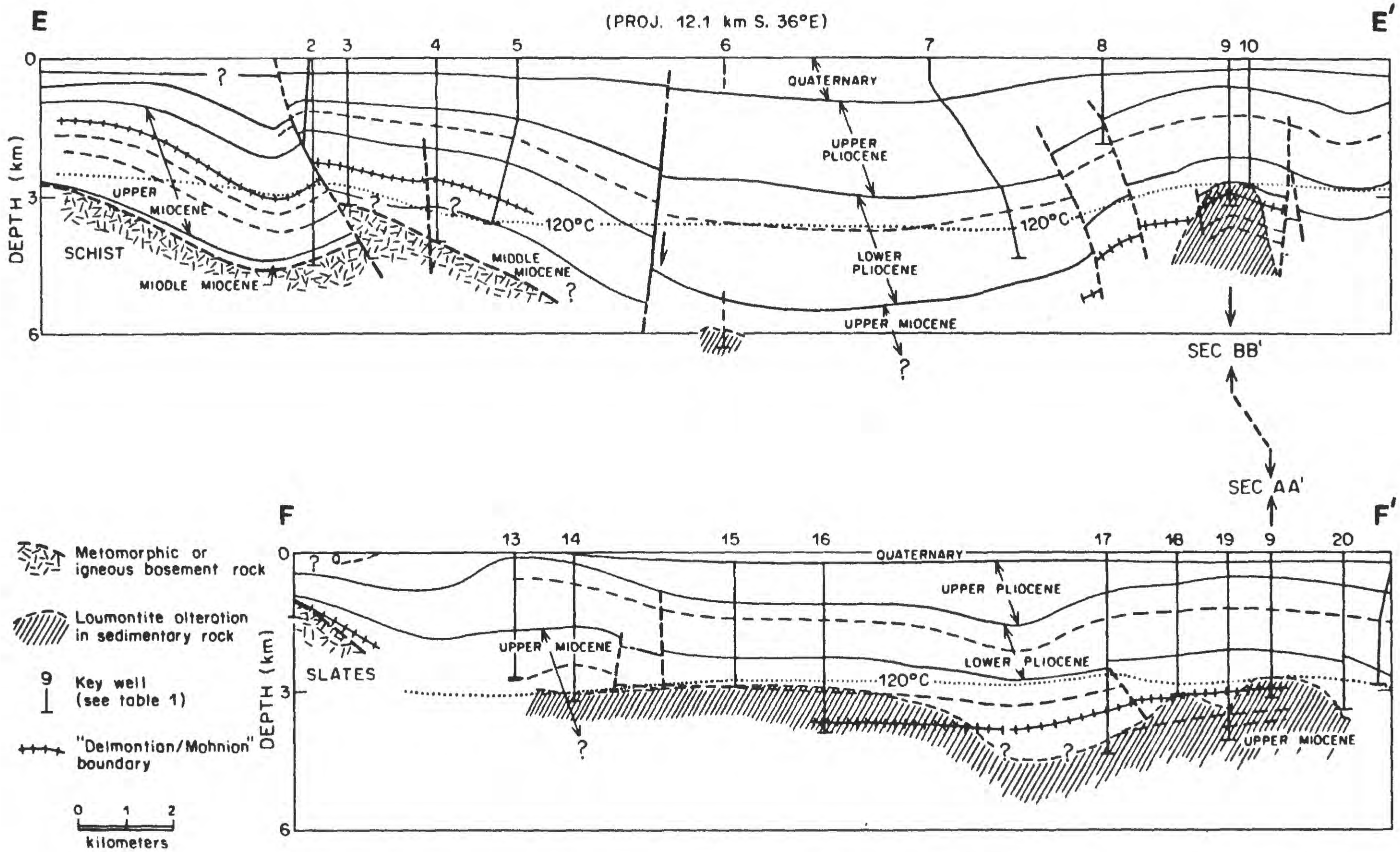

Figure 16. Structure sections EE' and FF' through central Los Angeles basin (McCulloh and others, 1978). Locations of sections are shown in figure 17. Top of laumontite alteration and 120° F isotherm are shown in sections.

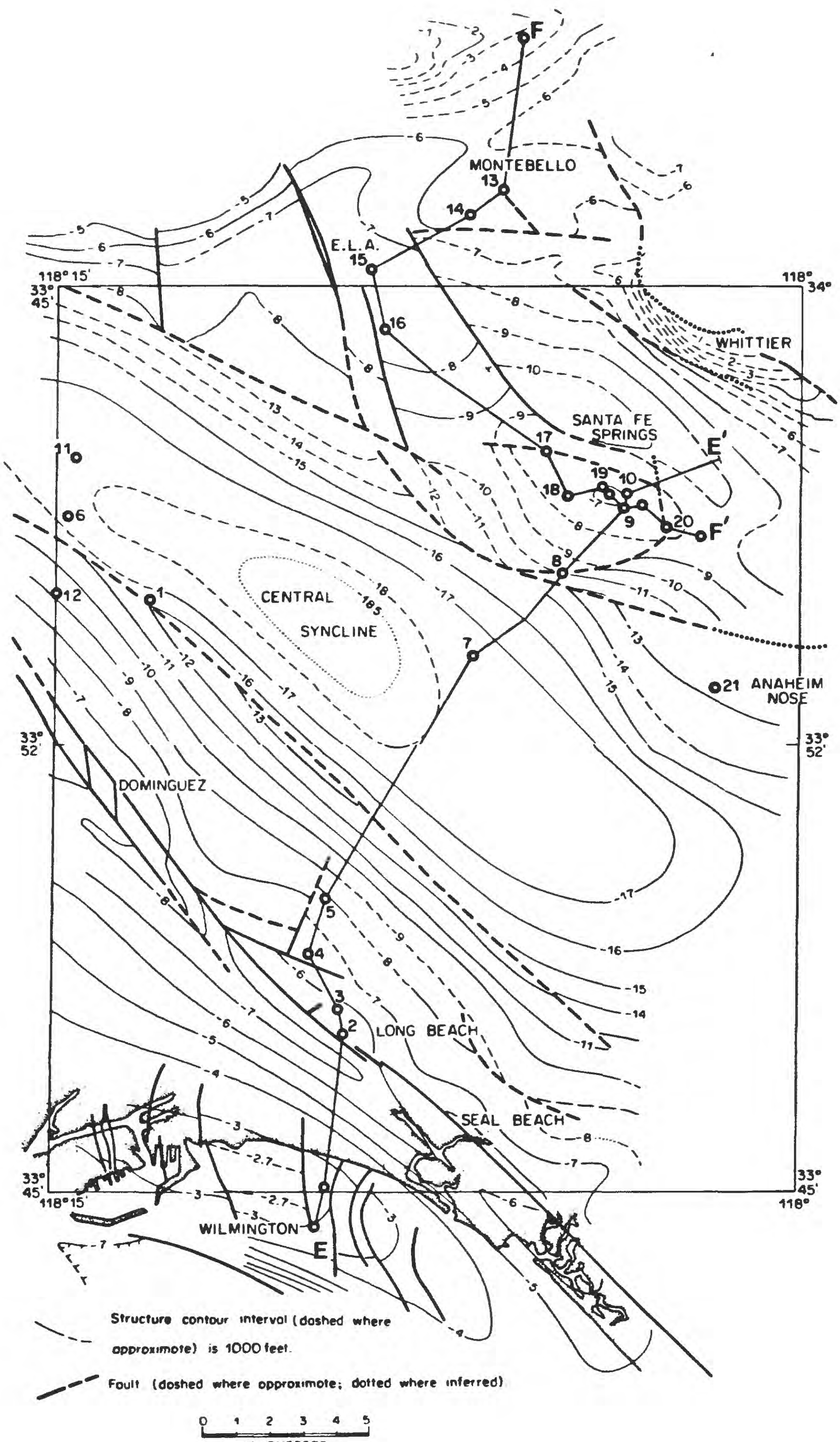

Figure 17. Structure contour map on base of Lower Pliocene, central Los Angeles basin (McCulloh and others, 1978). Locations of structure sections EE' and FF' (fig. 16) together with numbers of key wells (Table 1) also are shown.

Table 1. Key wells and exploratory holes shown in figures 16 and 17 (McCulloh and others, 1978)

Map Symbol (Figs. 16 & 17)	Operator (original), Lease, and Well No.
A	THUMS/Long Beach, Inc.--"Long Beach Unit Tract-1" D-630
B	Humble Oil and Refining Co.--"South San Gabriel Unit 1" 1
B[1]	Western Gulf--"Newgate Unit A" 1
1	Standard Oil Co. of Calif.--"Carlin Comm." 1
2	Shell Oil Co.--"Alamitos" 48-A
3	do. --"Dolley" 2
4	Texaco, Inc.--"Long Beach Airport" 1 (Redrill)
5	Standard Oil Co. of Calif.--"Weingart" 1
6	American Petrofina Exploration Co.--"Central Corehole" 2
7	Union Oil Co. of Calif.--"Union-APEX Norwalk-Bellflower" E.H. 2
8	General Petroleum Co.--"Comm. 14" 1
9	do. --"Santa Fe" 243 (Redrill)
10	General Petroleum Co.--"Santa Fe" 143-B
11	Western Gulf Oil Co.--"Pacific Electric Railway" 1
12	Calizoo Oil Co.--"Saulque" 1
13	Standard Oil Co. of California--"Baldwin" 82
14	Union Oil Co. of Calif.--"Howard and Smith" 3
15	Richfield Oil Corp.--"U. P. Unit-1" 1
16	Chanslor Canfield Midway Oil Co.--"Bandini" 1
17	Standard Oil Co. of California--"Houghton Comm. One" 1
18	Ed. Nepple--"S.P.-Pedro-Nepple" 2
19	Union Oil Co. of California--"Bell" 107
20	Standard Oil Co. of California--"Carmenita Comm." 1

Angeles basin than for similar-aged, more mineralogically mature sandstones, such as those of the Gulf Coast (compare fig. 18a with Berg, 1986, fig. 9-30). The porosity-depth gradient generally is greater where the present or past geothermal gradient is or has been greater (Dixon and Kirkland, 1985). However, some sandstone sequences of approximately equivalent age and burial history from different parts of the basin may have different porosity-depth gradients that cannot be explained solely by different burial temperature histories (fig. 18b; McCulloh and others, 1978).

PETROLEUM PLAYS

The play concept in the assessment of petroleum resources is defined as a group of hydrocarbon prospects and/or discovered accumulations that have common geological characteristics such as source rock, trapping mechanism, structural history or depositional pattern (Procter and others, 1982). Within a basin, play definition is a subjective process and different workers may define different numbers of plays based on different criteria. For the 1987 petroleum assessment of the Los Angeles basin province, three plays were defined primarily on the basis of geographic and structural setting. Because resource assessment by play analysis utilizes statistical data of discovered accumulations within the play, the need to logically group the discovered oil and gas reservoirs in the basin also influenced play definition.

PLAY I: Northwest Basin Flank Including Adjacent Offshore State Lands

This play encompasses the area south and southeast of the Malibu Coast-Santa Monica-Raymond Hill fault trend along the northwest flank of Los Angeles basin (figs. 4, 7 [section DD'] and 19). The eastern and southeastern boundary includes the western part of the northern shelf and excludes most of the San Gabriel Valley. The southern boundary of the play is drawn between the Cheviot Hills and the Inglewood fields where the axis of the central syncline turns westward (fig. 20). The play also includes the adjacent offshore state lands to the west that are bounded on the south by the three-nautical-mile (5.5-km) limit of state offshore lands. This offshore area, arbitrarily extended westward to Point Dume and generally bounded on the north by the Malibu Coast fault, contains numerous marine oil and(or) gas seeps (Wilkinson, 1972; Greene and others, 1975; Nardin, 1978).

Discovered oil reservoirs are sandstone sequences of Late Miocene and Early Pliocene age with a small amount of gas obtained from the upper Pliocene rocks in the Los Angeles Downtown field. In some cases, organic-rich shales encapsulate the channel-like turbidite sandstone reservoirs of Upper Miocene age that are part of the Tarzana fan complex sourced from north of the Santa Monica Mountains (Sullwold, 1960). Lower Pliocene sandstone reservoirs apparently are distal turbidite facies derived from submarine canyons that were located along the northeast margin of the Los Angeles basin (Conrey, 1967). Reservoirs have not been found in the Middle Miocene Topanga Formation or older rocks in this play area. Principal fields of this play and average reservoir depths and net thicknesses are given in Table 2.

Structural traps include west- to northwest-trending anticlines, faulted anticlines and faulted homoclines. Stratigraphic traps mostly are pinchouts on homoclines and lenticular sands. Traps near the Santa Monica fault zone occur in the footwall (south) block and are complex structures partly

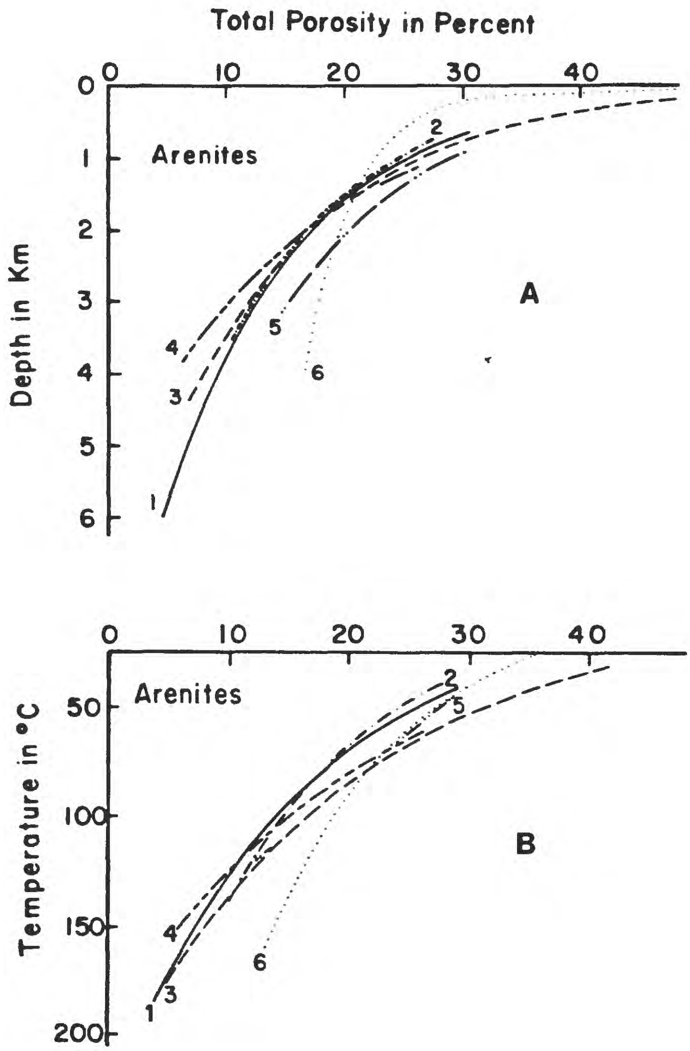

Figure 18. Porosity versus depth (A) and porosity versus temperature (B) for arenites from six well sites in the central Los Angeles basin (McCulloh and others, 1978). Site locations are (1) Los Angeles central syncline, (2) Anaheim nose, (3) Santa Fe Springs oil field, (4) East Los Angeles oil field area, (5) Santa Fe Springs southern flank, and (6) Long Beach-Dominguez-Seal Beach area. Curves of the form porosity = A + B log Z, where Z is depth or temperature, were fit to large sets of porosity data from locations where depth of burial and temperature have never been greater.

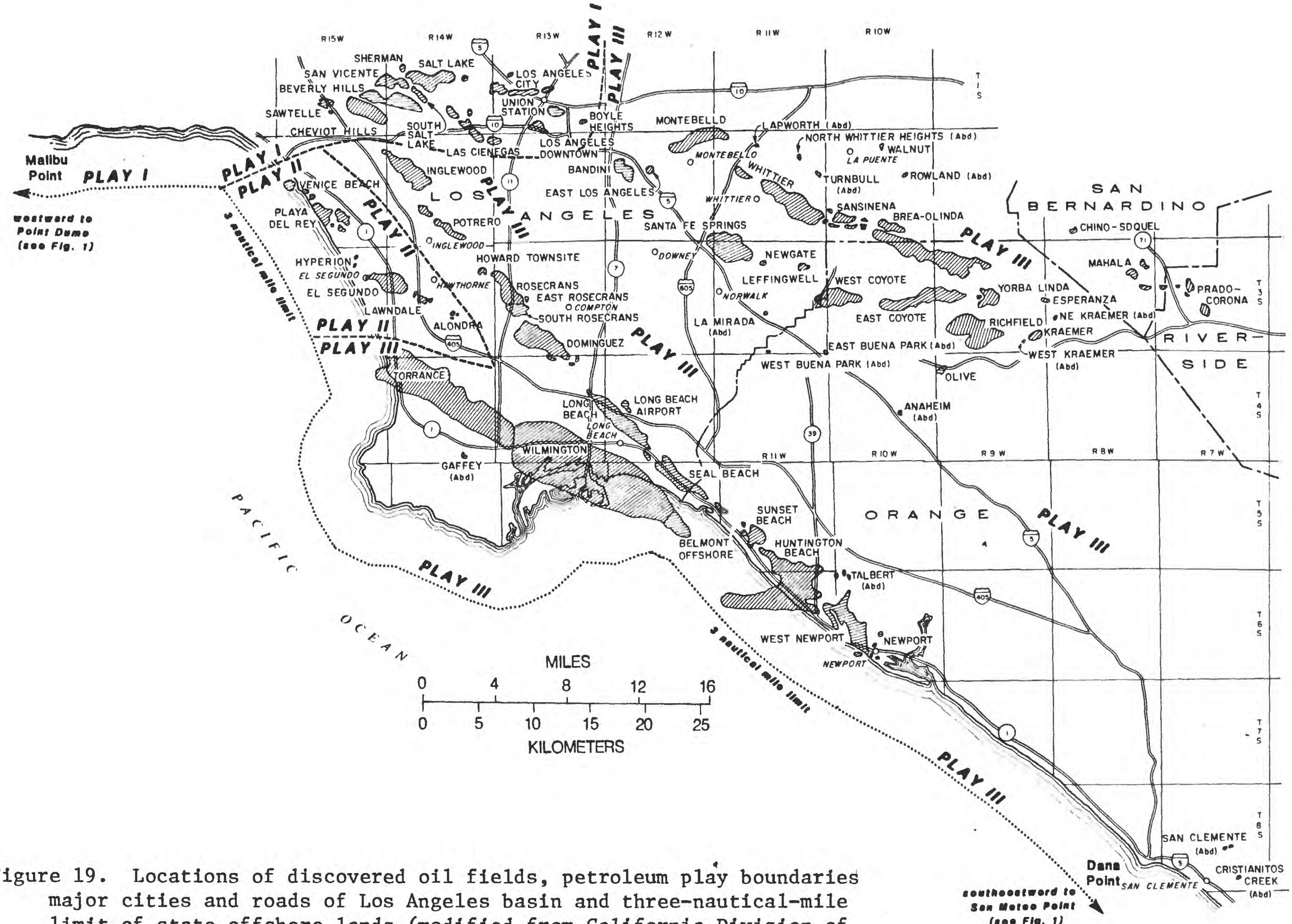

Figure 19. Locations of discovered oil fields, petroleum play boundaries major cities and roads of Los Angeles basin and three-nautical-mile limit of state offshore lands (modified from California Division of Oil and Gas, 1976).

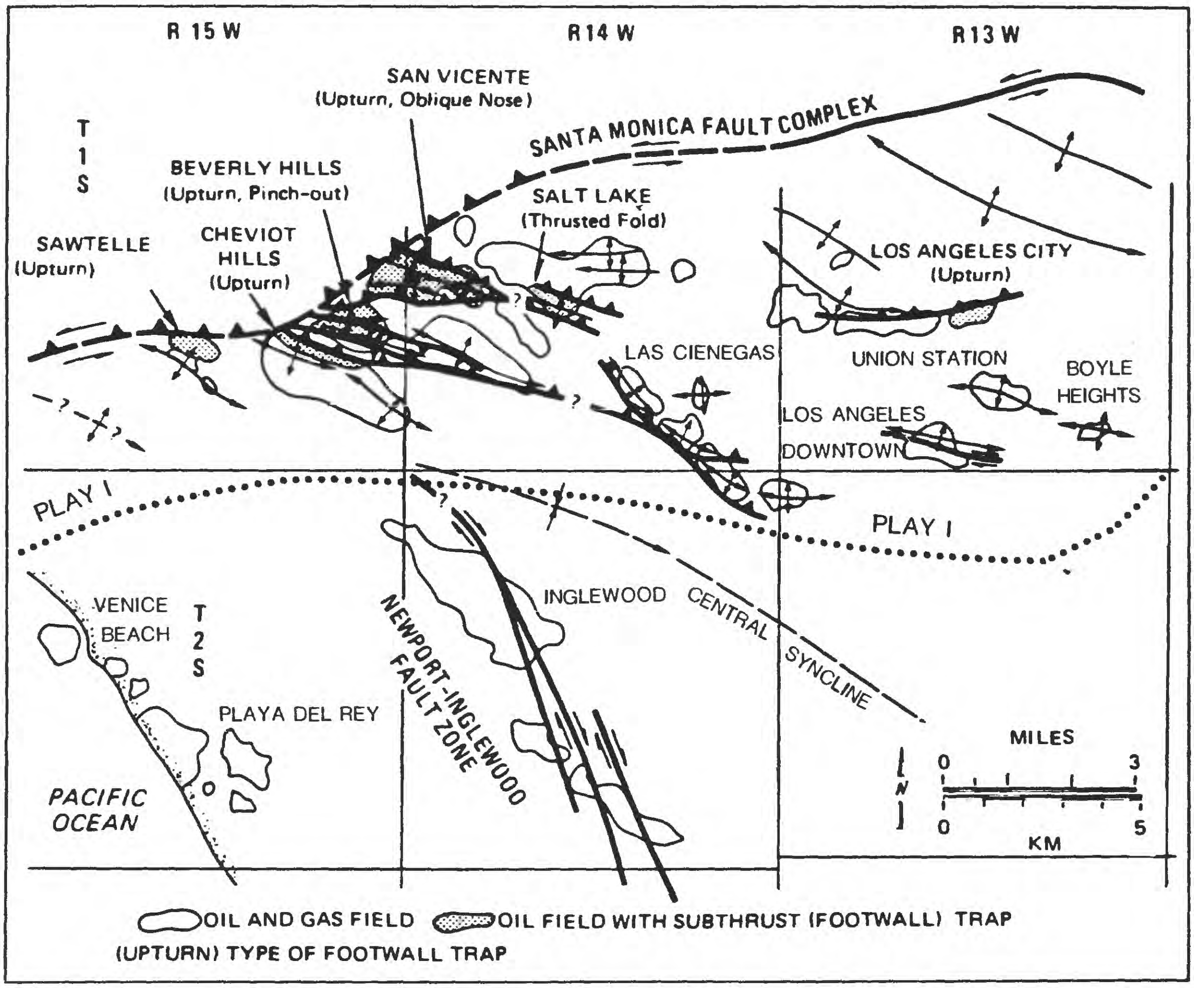

Figure 20. Main structures of the Santa Monica fault trend and adjacent northwest flank of Los Angeles basin (Harding and Tuminas, 1988). Trend consists of left-stepping en echelon anticlines and en echelon reverse faults that parallel anticlines. Portion of southern boundary of PLAY I also is shown. By permission of American Association of Petroleum Geologists.

Table 2. Principal oil fields and depths and net thicknesses of discovered oil reservoirs by play. Data from California Division of Oil and Gas (1974, 1987)

Principal oil fields	Range of average depths of discovered oil reser- reservoirs[1]	Range of net thickness of discovered oil reservoirs[1]
PLAY I		
Beverly Hills, Las Cienegas, Salt Lake, Cheviot Hills, Los Angeles City, San Vicente, Sawtelle, Los Angeles Downtown, Salt Lake South	275 - 3,290 m 900 - 10,800 ft	10 - 610 m 30 - 2,000 ft
PLAY II		
Playa del Rey, El Segundo, Venice Beach, Lawndale, Alondra	455 - 2,745 m 1,490 - 9,000 ft	5 - 90 m 15 - 300 ft
PLAY III		
Southwest of central syncline axis		
Wilmington, Huntington Beach, Long Beach, Inglewood, Dominguez, Torrance, Seal Beach, Rosecrans, Newport West, Belmont Offshore	290 - 2,970 m 950 - 9,750 ft	5 - 365 m 15 - 1,200 ft
Northeast of central syncline axis		
Santa Fe Springs, Brea-Olinda, West Coyote, Richfield, Montebello, East Coyote, Yorba Linda, Sansinena, Whittier	275 - 3,625 m 900 - 11,900 ft	6 - 275 m 20 - 900 ft

[1] Average depth and average net thickness of individual reservoirs were summarized mostly from California Division of Oil and Gas (1974) and various issues of the Summary of Operations--California Oil Fields published by the California Division of Oil and Gas.

involving overturned folds (Eschner and Scribner, 1972; Engineer and others, 1985; Harding and Tuminas, 1988). Other traps on the western part of the northern shelf are related to generally east-west-trending reverse faults that dip steeply toward the north (Lang and Dreessen, 1975).

Oil has migrated into these upper Miocene and lower Pliocene sandstone reservoirs from the organic-rich basal unit ("nodular shale") of the Modelo Formation which is believed to have sourced most of the reservoired oil in the northwest part of the Los Angeles basin (Hoots and others, 1935; Philippi, 1965; Walker and others, 1983).

The eastern part of this play is moderately well explored, but down-dip areas to the south toward the central basin syncline remain largely untested (Stark, 1972). The western part of the onshore area is somewhat less well explored, largely because of restraints caused by heavy urbanization. At least one significant prospect in this area has remained undrilled for 18 years (Oil and Gas Journal, 1985). In the western offshore part of the play, a drilling moratorium has been in effect since the late 1960's, and few exploration wells have been drilled there (fig. 21).

PLAY II: Playa del Rey Platform and Adjacent Offshore State Lands

This play includes the area southwest of the northern part of the Newport-Inglewood zone of deformation, northwest of the Palos Verde Hills plus the adjacent offshore state lands (figs. 19 and 1). Numerous marine oil and(or) gas seeps are present in the offshore area and adjacent federal waters (Wilkinson, 1972; Greene and others, 1975; Nardin, 1978).

Discovered oil fields occur along a northwest-trending ridge in the schist basement on the northwest shelf of the Los Angeles basin (figs. 1 and 4). Reservoirs occur in the fractured and weathered schist basement, schist conglomerate overlying the basement and, to a minor extent, in marine sandstones of the uppermost Miocene and lower Pliocene sequence. The sparse marine sandstones in this play represent very distal facies of turbidite sequences derived beginning in latest Miocene from sediment source areas located to the north and northeast across the in-filling central syncline.

Reservoir traps include (1) faulted domes and anticlines that seem to involve basement folding, (2) fractured and weathered basement rocks, (3) lenticular sands and (4) overlapped sand lenses. Principal fields of this play and average reservoir depths and net thicknesses are given in Table 2.

The organic-rich shale of the basal unit ("nodular shale") of the Upper Miocene sequence is believed to be the principal source rock for both underlying reservoirs in fractured schist and schist conglomerate and overlying Upper Miocene and lower Pliocene sandstones (Hoots and others, 1935; Philippi, 1965; Walker and others, 1983). Oil has migrated from onlapping Upper Miocene strata into the older but structurally higher schist basement and conglomerate (Yerkes and others, 1965). The onshore part of this play is well explored. A moratorium against offshore exploratory drilling has been in effect since the late 1960's in this area, making the offshore region less well explored (fig. 21).

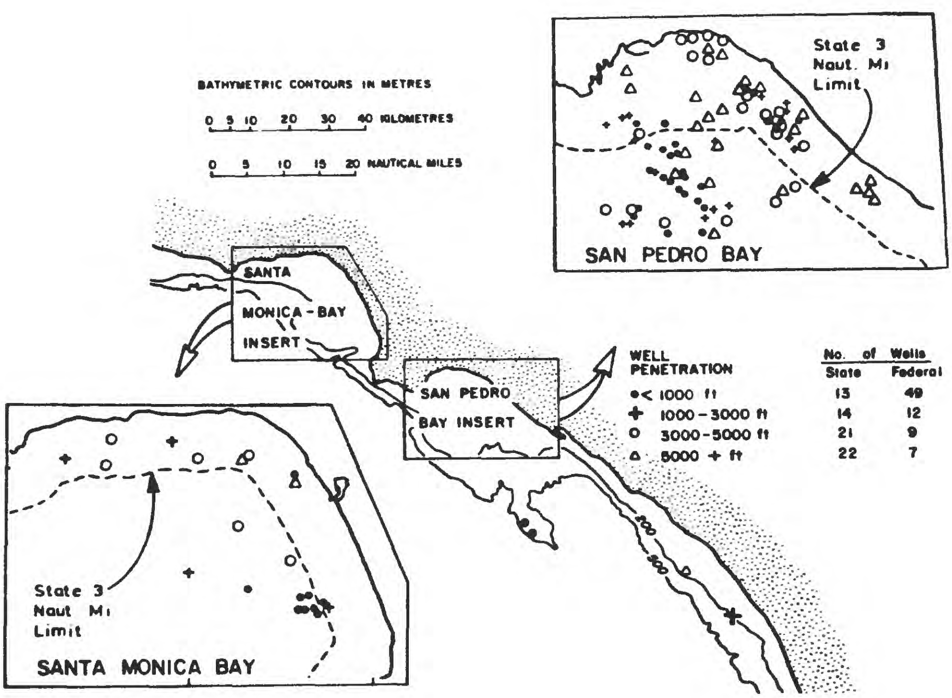

Figure 21. Core holes and stratigraphic test wells drilled in state and adjacent federal offshore lands of Santa Monica and San Pedro Bays prior to U.S. Supreme Court ruling on state-federal offshore boundary in January 1966 (adapted from Taylor, 1976).

PLAY III: Main Los Angeles Basin and Areas to the North, East and South

This play encompasses the remainder of the Los Angeles province not included in plays I and II. It is discussed in two parts that coincide with areas that are separated by the axis of the central syncline of the basin and its eastward extension (figs. 19 and 4).

Area south of central syncline axis including adjacent offshore state lands

Discovered oil fields in this part of Play III lie along the northwest-trending Newport-Inglewood zone of deformation and along the adjacent sub-parallel Torrance-Wilmington anticlinal trend (figs. 19 and 4).

Reservoirs occur mostly in sandstone units of the Upper Miocene and lower Pliocene sequence, although some production is obtained from the Middle Miocene rocks (Inglewood and Sunset Beach fields) and from fractured schist basement (Wilmington field). Abundant marine sandstones in this play area are turbidite deposits derived from source areas to the north, northeast and east. Reservoir traps are predominantly faulted anticlines with lesser numbers of fault and stratigraphic traps on noses and homoclines. Principal fields of this play and average reservoir depths and net thicknesses are given in Table 2.

Organic-rich shales of late Middle to Late Miocene, and possibly lower Pliocene age, are believed to be the source for reservoired oil in this play. Oil has migrated principally southwestward from the central syncline, although deeply buried, organic-rich shales in the vicinity of the oil fields also may have contributed.

Upper Miocene and younger rocks have been adequately explored along the Newport-Inglewood zone from the Inglewood oil field to the Newport West field, except for possible deep-pool extensions and down-dip traps on the southern flank of the central syncline (Yerkes and others, 1965). The offshore area of state lands is less well explored (fig. 21), particularly along the offshore extensions of the Palos Verdes fault zone and its associated structures in San Pedro and Santa Monica Bays (Junger and Wagner, 1977) (fig. 22). Pre-Miocene rocks, particularly of Eocene age, might be prospective between the San Joaquin Hills and the northwest end of the buried Anaheim nose (Yerkes and others, 1965). The southeast part of this play, including the San Joaquin Hills is less well explored, but appears less favorable because of its greater distance from source rocks of the central syncline area, absence of abundant sandstones of Upper Miocene and lower Pliocene age that form oil reservoirs in other parts of the basin and lower porosity of pre-upper Miocene rocks (Yerkes and others, 1965; Stark, 1972).

Area north of central syncline axis including San Gabriel Valley, Chino basin and eastern shelf

Discovered oil fields in this part of Play III are located on (1) the northwest-plunging Anaheim nose (minor Anaheim, Buena Park East and West, and La Mirada fields), (2) the westerly extension(?) of the El Modeno fault (minor Olive field), (3) the west- to northwest-trending Coyote Hills uplift and its southeast flank (Richfield, Yorba Linda, East Coyote, West Coyote, Santa Fe Springs and adjacent minor fields), (4) the Whittier fault zone (Brea-Olinda,

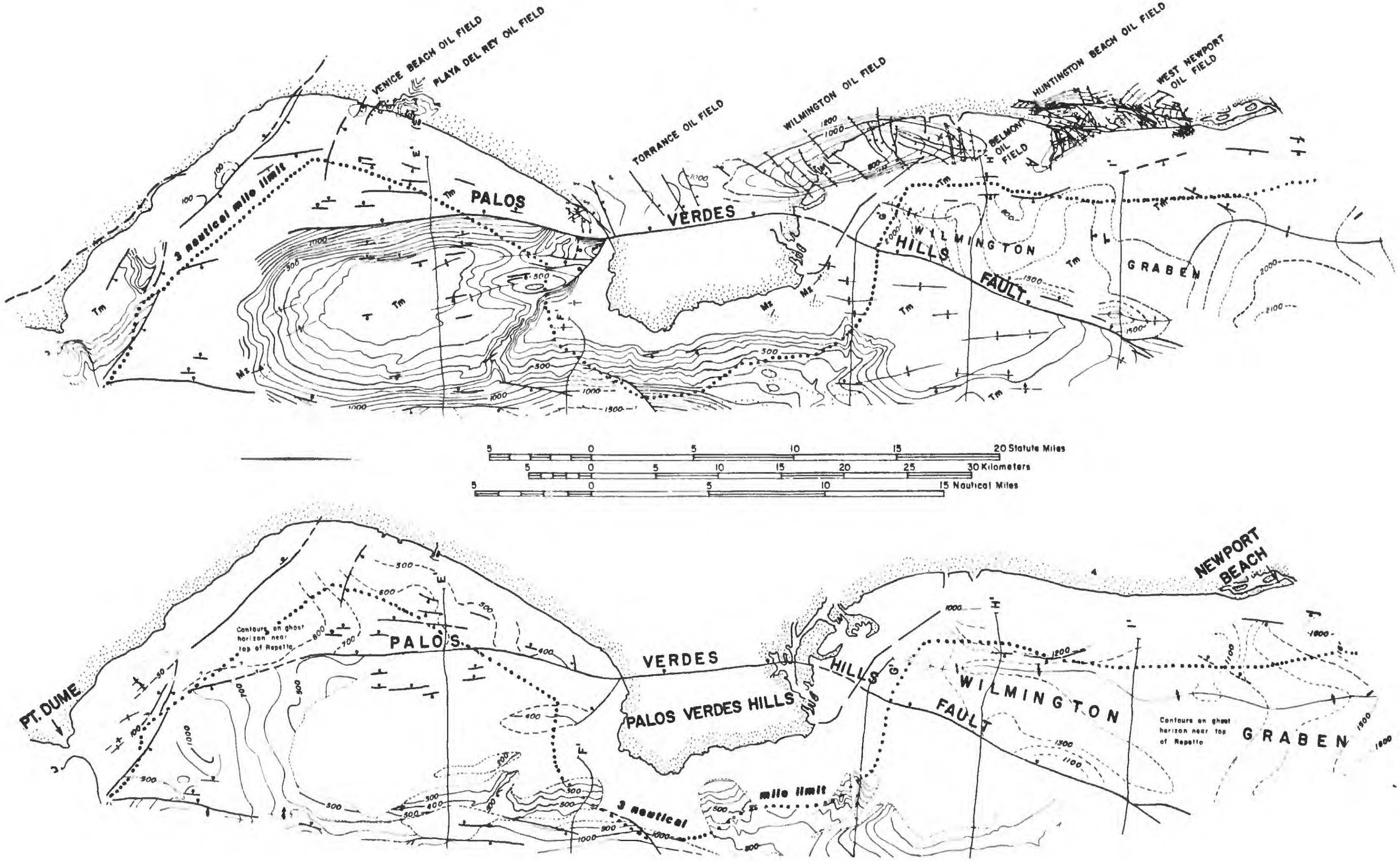

Figure 22. Map of offshore area from Point Dume to Newport Beach (Junger and Wagner, 1977). Structure contours on lower Pliocene strata (Repetto formation of local usage) (bottom) and on late Miocene to early Pliocene unconformity (top).

Sansinena, Whittier and minor Esperanza fields), (5) the Chino fault and basin (minor Prado-Corona, Mahala and Chino Soquel fields), (6) the Puente Hills north of the Whittier fault zone (minor Rowland, Walnut, Turnbull, North Whittier Heights and Lapworth fields), and (7) the eastern part of the northern shelf (Montebello and minor East Los Angeles and Bandini fields) (figs. 1 and 19).

Oil reservoirs are mostly sandstones of Upper Miocene and lower Pliocene age. Several minor oil reservoirs have been discovered in Pleistocene sandstones (Yorba Linda field), upper Pliocene sandstones (Anaheim and Santa Fe Springs fields) and middle Miocene sandstones (Brea-Olinda field). Reservoir traps consist mostly of faulted anticlines, faulted noses, various stratigraphic traps, faults, and several domes. Principal fields of this play and average reservoir depths and net thicknesses are given in Table 2.

Reservoir rocks include a variety of marine facies that range from distal turbidite sandstones to proximal conglomeritic sandstones. Conrey (1967) and Gourley (1975) have studied lithofacies of these Upper Miocene and lower Pliocene rocks in parts of the play area and concluded that submarine fans prograded southward and westward through the play area starting in Late Miocene time. Similar conclusions were reached from unpublished proprietary studies (Redin, 1984; Wright, 1987b).

Upper Miocene and younger rocks have been thoroughly explored in much of this part of Play III except for (1) possible deeper pools and deep pool extensions of some discovered fields, (2) some down-dip areas along the northern flank and east end of the central syncline, (3) some down-dip areas and pre-upper Miocene sections on the Anaheim nose, (4) northwestward extensions of major fault zones such as the Pelican Hill and Shady Canyon faults, and (5) the eastern part of the northern shelf including the embayment between the East Los Angeles, Santa Fe Springs and Montebello fields (figs. 1, 4 and 19. Only five exploratory wells in the central syncline area have reached depths of 15,000 ft (4,572 m) or more.) Also, the San Gabriel Valley, West and East Puente Hills, Chino Hills, Chino basin and basin margin west of the Santa Ana Mountains have not been thoroughly drilled and offer possible likelihoods for discovery of mostly small reservoirs (Yerkes and others, 1965; Stark, 1972; Green and Castro, 1973).

Very small, subcommercial oil accumulations have been discovered in the now-abandoned San Clemente and Cristianitos fields, east of Dana Point (fig. 19). The oil reservoirs are Upper Cretaceous sands near the Cristianitos fault zone. It is possible that other Upper Cretaceous through lower Miocene sandstones in the extreme southeast part of the Los Angeles province could reservoir small amounts of oil if suitable pathways from Middle Miocene source rocks have existed (Wright, 1987b). The timing of maturation of petroleum fluids and Neogene crustal kinematics (especially translational motions) seem crucial to the determination of oil accumulations at locations presently so remote from known source rocks. Probabilities for significant petroleum resources in this extreme southeast part of the Los Angeles province and farther south toward San Diego presently are very low to negligible.

PETROLEUM DEVELOPMENT

The history of commercial petroleum exploration and production in the Los Angeles basin dates back at least to the 1880's and has been summarized in numerous publications (e.g., Wright, 1987c). Discovery dates, descriptions of oil and gas reservoirs and production data are available from various sources, but especially from publications and annual reports of the California Division of Oil and Gas, and the Conservation Committee of California Oil Producers. Only a brief summary of the petroleum development of the Los Angeles basin is presented here.

Cumulative production and estimated reserves of oil, condensate and natural gas totaled slightly more than 10 billion barrels at the end of 1986 after gas is converted to energy-equivalent barrels of oil (BOE) (Table 3). About seven-eighths of the estimated recoverable oil and condensate, and most of the estimated recoverable natural gas had been produced at the end of 1986 (Table 3).

During the ten-year period from 1977 through 1986, no new fields were discovered and less than 35 MMbbls of recoverable oil was discovered in new field areas and new pools in the Los Angeles basin (Department of Energy, 1978-1987). However, during this same period, estimated oil reserves (prior to subtraction of production) increased by 715 MMbbls (California Division of Oil and Gas, 1977-1987) due to upward revision of estimated reserves of large fields in response to reservoir extensions and production increases brought about mostly by improved and expanded recovery techniques. Reserve increases during this period came mostly from the Wilmington (385 MMbbls), Inglewood (70 MMbbls), Huntington Beach (54 MMbbls), Brea-Olinda (52 MMbbls), Beverly Hills (36 MMbbls), Torrance (34 MMbbls), Richfield (23 MMbbls), Seal Beach (14 MMbbls), and Coyote East (11 MMbbls) fields. During this period 834 MMbbls of oil was produced, yet estimated reserves at the end of 1986 were only 119 MMbbls (California Division of Oil and Gas, 1977-1987) less than at the end of 1976. Further increases in estimated reserves are expected if improved and expanded recovery techniques continue to be applied to the larger fields of the basin (e.g., Wallace (1979), Shuler and others, 1985; Katz, 1987, Morrissey and others, 1988).

DISCUSSION

This report supported the 1987 petroleum assessment of the Los Angeles basin by providing (1) a geological summary of the basin, (2) brief summaries of the thermal regime, source rocks, reservoir diagenesis and porosity, and petroleum development, and (3) definitions and descriptions of three petroleum plays used in the assessment procedure. Many excellent papers are published that provide more detail of the subjects summarized here (see References).

Petroleum play definition is a subjective process, and different workers may define, with equal validity, different plays based on different criteria. The criteria used here to define plays is given at the beginning of the PETROLEUM PLAYS section (p. 32). After play definition, the Nehring (1986) data base of estimated recoverable oil and gas from discovered oil and gas fields of the basin was allocated by play. Play names and estimated recoverable oil and gas from known accumulations are given in Table 4. Later steps in the petroleum assessment procedures are beyond the purview of the

Table 3. Cumulative production and estimated reserves of oil and condensate, and associated plus nonassociated gas in the Los Angeles basin at the end of 1986, expressed in billions of barrels of oil (BBO) and trillions of cubic feet (Tcf). Cumulative production and estimated reserves expressed as percent in right column. Figures are rounded off from California Division of Oil and Gas (1987)

Oil and condensate		
cumulative production	7.79 BBO	88%
estimated reserves	1.06 BBO	12
total	8.85 BBO	100
Associated and nonassociated natural gas		
cumulative production	7.27 Tcf	96%
production estimated reserves	0.32 Tcf	4
total	7.59 Tcf	100
Total oil, condensate, natural gas[1]		
cumulative production	9.00 BBO	89%
estimated reserves	1.11 BBO	11
total	10.11 BBO	100

[1]Natural gas is converted to energy-equivalent barrels of oil using 6 Mcf = 1 bbl.

Table 4. Estimated recoverable oil (including condensate) and natural gas by petroleum play expressed as percent of estimated recoverable oil and natural gas in Los Angeles basin. Cumulative production and estimated reserves as of the end of 1986 (California Division of Oil and Gas, 1987)

Petroleum Play	Cumulative production plus estimated reserves expressed as a percent of basin total: oil and condensate	Cumulative production plus estimated reserves expressed as a percent of basin total: associated and nonassociated natural gas
I: Northwest basin flank including adjacent offshore state lands	9%	5%
II: Playa del Rey platform and adjacent offshore state lands	1%	1%
III: Main Los Angeles basin and areas to the north, east and south		
A. Area south of central syncline axis including adjacent offshore state lands	60%	70%
B. Area north of central syncline axis including San Gabriel Valley, Chino basin and eastern shelf	30%	24%

author, and the reader is referred to Houghton (1987), Crovelli (1988), and Mast and others (1988).

The seemingly insignificant area of the Los Angeles basin compared to other U.S. petroleum provinces belies the fact that it has been one of the most important oil-producing regions of the country. If categorized as a state, the Los Angeles basin produced in 1986 as much oil as Montana and more than Illinois or Michigan (California Division of Oil and Gas, 1987; Oil and Gas Journal, 1987). Los Angeles basin ranks behind only Texas, Louisiana, Oklahoma, and California in cumulative oil production through 1986, and behind only Alaska, Texas, Louisiana, and California in estimated reserves at the end of 1986 (Department of Energy, 1987; California Division of Oil and Gas, 1987; Oil and Gas Journal, 1987). From 1977 through 1986 the increase in estimated recoverable oil of the Los Angeles basin (due primarily to field revisions and extensions) was about 715 MMbbls--greater than the increase in estimated recoverable oil over the same period of New Mexico, North Dakota, Montana, or Colorado (California Division of Oil and Gas, 1987; Department of Energy, 1978-1987). As stated previously, the Los Angeles basin ranks first in the world in terms of total discovered oil-in-place per unit basin volume (McFarland and Greutert, 1971; Perrodon, 1972).

In spite of the impressive position of the Los Angeles basin among oil-producing states of the U.S., discovery of new oil fields in the basin has not been an important contributor to increases in recoverable oil for more than two decades. However, sizeable increases in recoverable oil over the next several decades should occur, as estimated reserves of large, known fields continue to be revised upward in response to production increases generated by pool extension and improved and expanded recovery techniques.

The Los Angeles basin province is by far the most heavily urbanized oil-producing region in the U.S. This urbanization has progressively perturbed the exploration and discovery rates for at least three to four decades. Although some notable cooperation has occurred (e.g., Wright, 1987c; Wright and Heck, 1987; Jacobsen and Lindblom, 1987), pressures against petroleum exploration and development are great (e.g., Oil and Gas Journal, 1985; Wright, 1987c). Inaccessibility and(or) high evaluation of land in the Los Angeles basin province will continue to adversely affect exploration for new petroleum resources, enhanced recovery operations and oil property abandonment decisions for the foreseeable future.

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