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January 14, 2002

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STRATIGRAPHIC EQUIVALENTS OF THE WILMINGTON FIELD "TAR ZONE" IN THE SUBSURFACE LOS ANGELES BASIN, CALIFORNIA

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ABSTRACT

A seven-year thermal project in "old Wilmington" field (Los Angeles basin) for the "Tar zone" is part of a technology-transfer program by the United States Department of Energy (U.S. DOE) which proposes to transfer successful new techniques to other oil and gas producers operating reservoirs comprised by sediments exhibiting similar conditions of heterogeneity and depositional environment. The present form and structural relief of the Los Angeles basin were established during late Miocene time. Most of the area consisted of marine slope-to-basin environments during late Miocene and early Pliocene time. The basin is divided into four structural blocks with major zones of faulting in the basement rocks at the contacts between blocks. The fault systems bounding the blocks have allowed each block to have a different subsidence history and basement configuration.

The Los Angeles basin is filled with a monotonous succession of alternating sand, silt and shale bodies. There are no distinctive "marker beds" which can be recognized and correlated in the subsurface over any significant distance. Benthic foraminiferal assemblages provide the primary correlation tool for middle Miocene to Pleistocene strata in the basin. The "Tar zone" is defined as in "old Wilmington" field to extend from Wilmington markers S through F_1/F_O. This interval is identified as comprising most of the middle Repettian stage, excluding the uppermost and lowermost portions. Relatively recent published regional cross-sections which allow the middle Repettian stage to be identified provide the basic framweork for correlation of the "Tar zone" with stratigraphic equivalents across the Los Angeles basin. Benthic microfaunal zones are used as though they mark time lines because, although such zones are time-transgressive due to the influence of water depth, for the subsurface Los Angeles basin most of the critical correlations are within the same environment (basin plain).

Migration pathways and reservoirs in the Los Angeles basin are dominated by Miocene and Pliocene turbidites and associated deep-water facies. Repettian-stage percent sandstone and conglomerate lithofacies and submarine-fan facies maps allow identification of generalized marine depositional environments and clastic source areas for "Tar zone" stratigraphic equivalents (if present) in approximately 70 oil and gas fields in the Los Angeles basin. Results of the U.S. DOE field demonstration program will be directed toward operators in fields with productive "Tar zone" stratigraphic equivalent units.

INTRODUCTION

The United States Department of Energy (U.S. DOE) has instituted an oil and gas research program which involves technical joint ventures and cost sharing with industry for a focus on technology transfer of successful new techniques to other producers operating similar reservoirs. The program goal is to find better recovery methods for the most common U.S. reservoir types. The first group of projects targeted fluvial-dominated deltaic-sand reservoirs and the second group involved shallow-shelf carbonate reservoirs.

The Class III program focuses on slope-and-basin clastic reservoirs. For these deep-marine reservoirs, most projects involve fields in Texas and California. A seven-year thermal project was proposed in the "Tar zone" on the southern half of fault block II-A in Wilmington field, California. Participants are the City of Long Beach, Tidelands Oil Production Company, University of Southern California, and David K. Davies & Associates, Inc. of Kingwood, Texas.

Wilmington field is located in the southwestern portion of the Los Angeles basin, as shown on Figure 1. The Los Angeles basin at present has approximately 70 oil and gas fields, all of which are identified on Figure 1 with the exception of Beta, which is located about nine miles offshore (Wright, 1987b), southwest of Huntington Beach. Wilmington field is comprised by ten major fault blocks (fault blocks I to VIII and blocks 90S and 90N), as shown on Figure 2. Fault block II-A is located in the portion of the field which was developed during its early history, west of the Daisy Avenue-Golden Avenue fault system; this area is commonly called "old Wilmington."

The Problem

The DOE field demonstration program is testing the theory that oil reservoirs comprised by sediments laid down under conditions of the same depositional environment will have similar production problems related to heterogeneity. Lack of awareness and access to technology and information has been shown to be a significant problem for U.S. oil and gas producers, particularly independent operators. Since the main thrust of the DOE program is technology transfer, participants in the Wilmington fault block II-A "Tar zone" study wished to identify the existence of stratigraphically-equivalent intervals in all other fields in the Los Angeles basin. All operators of wells in fields with producing "Tar zone" stratigraphic equivalents, particularly those intervals deposited under similar conditions, will be targeted for inclusion in the local technology transfer network established to disseminate results of all DOE studies in the Los Angeles basin. The local network is a subunit of the State-organized regional network; all participants then assume responsibility for the effectiveness of an aggressive national oil-and-gas-industry information and technology transfer network.

BACKGROUND

The present-day Los Angeles basin is a small topographic and structural basin with a very thick, dominantly Neogene sedimentary fill (Biddle, 1991). The older, depositional, basin was considerably larger than the present-day basin and underwent a multiple development history, each significant phase of which contributed to the hydrocarbon productivity of the area (Yerkes, et al., 1965; Wright, 1991; Yeats and Beall, 1991). There is general agreement among researchers that the Los Angeles basin formed in the middle and late Miocene to early Pliocene by extension associated with the evolving fault system between the North American and Pacific plates (Biddle, 1991; Mayer, 1991).

The Los Angeles basin is the most productive in the world in terms of hydrocarbons per volume of sedimentary fill. The organic-rich source rocks (middle to late Miocene Modelo, Monterey, and Puente formations) are part of an extensive succession of Miocene and lower Pliocene organic-rich and diatomaceous rocks common around the rim of the north Pacific ocean. Controls on the deposition of these rocks involved a very large area and thus are not related to the formation of any single basin (Biddle, 1991; Blake, 1991). The Modelo (Santa Monica mountains) and Puente (Puente hills, Santa Ana mountains, subsurface Los Angeles basin) formations are roughly age-equivalent to the Monterey formation (Palos Verdes and San Joaquin hills), but have higher clay and less organic content than is characteristic of Monterey (Wright, 1987a; Blake, 1991). Preservation of the organic matter is thought to be related to the geometry of the basin (trough-like with a

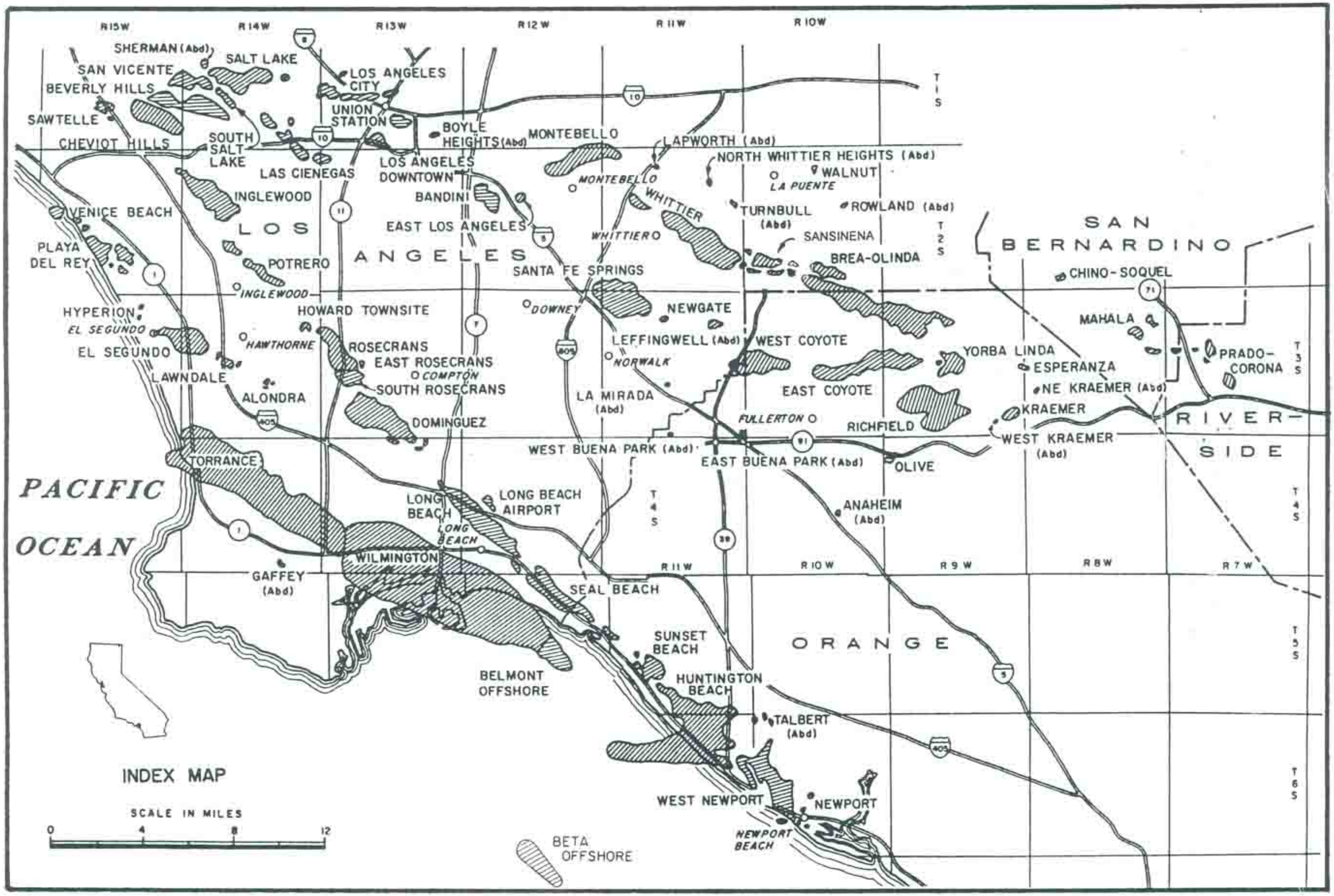


Figure 1. Location map for oil and gas fields of the Los Angeles basin. Adapted from California Division of Oil and Gas (1991).

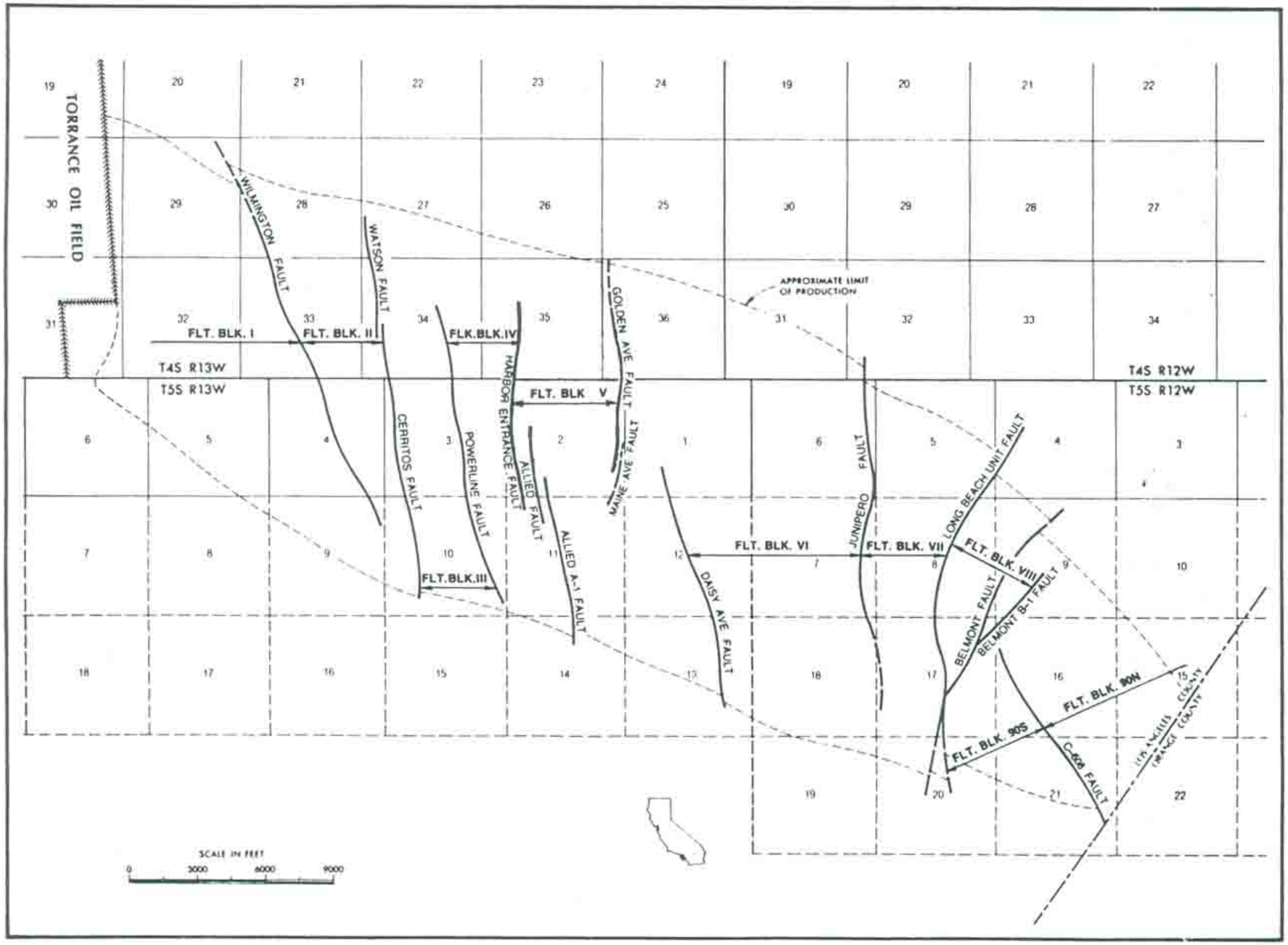


Figure 2. Wilmington oil field, Los Angeles County, California, showing fault blocks. Adapted from Crowder (1978).

narrow deep depocenter), bathymetry, the presence of sills, restricted circulation, and oxygen-deficient bottom waters (Gorsline and Emery, 1959; Henry, 1987; Blake, 1981, 1991).

Oil gravities are highly variable, ranging from less than 10E API in shallow producing zones to condensate (over 50E API) in a few deep fields; however, most oil produced in the basin is less than 25E API. Oil quality varies geographically, with higher quality oils (high API gravity, low sulfer content) in the northeast and lower quality in the west and south. Jeffrey, et al. (1991) theorized that higher quality is not caused by differences in kerogen type, but rather by higher maturity, greater migration distance, a more oxidizing depositional environment of the source rock, or a combination of all three. Depth-related variations in oil quality within the same field appear to be caused by biodegredation. With decreasing depth, there is a decrease in API gravity, an increase in sulfer concentration, a loss of saturated hydrocarbons and an increase in the carbon dioxide concentration in associated gas (Jeffrey, et al., 1991).

Previous Work

The Los Angeles basin has been extensively researched with many published studies dating to the 1850s of its geologic and tectonic setting. Yerkes, et al. (1965) presents a chronological list of significant papers from 1857 through 1962. Henry (1987) incorporates a bibliography for the Los Angeles basin and a series of paleogeographic diagrams based on the work of Woodring et al. (1946). Beyer (1988) includes a lengthy reference list for an assessment by the United States Geological Survey (USGS) of undiscovered recoverable petroleum resources in the Los Angeles basin. The most recent and comprehensive work is Memoir 52, published by the American Association of Petroleum Geologists (AAPG) in 1991. This volume is a source book for previously difficult-to-find and/or proprietary information with considerable detail on structure, biostratigraphy, geochemistry, stratigraphy and the evolution of submarine-fan systems in the basin with time.

The doctoral dissertation of Conrey (1959) is still the most detailed regional study of the sedimentary history of the early Pliocene in the Los Angeles basin. This work was published in somewhat simplified form by the California Division of Mines and Geology (CDMG) in 1967 as Special Report 93. Conrey (1959, 1967) provides separate isopach and lithofacies maps for lower, middle and upper early Pliocene strata. Lithofacies for Redin's (1991) Repettian-stage submarine-fan model are generalized over the entire early Pliocene; this model updates, but is compatable with, Conrey's (1959, 1967) more detailed work.

Regional Setting

The Los Angeles basin is located at the juncture of the Transverse Ranges physiographic province to the north, the Peninsular Ranges province to the south and east, and the continental borderland to the west (Wright, 1991). The physiographic Los Angeles basin is a coastal plain gently sloping toward the sea. It overlies the larger structural depositional Los Angeles basin, which attained its maximum reach during the middle and late Miocene when it extended east into the San Gabriel valley and north across the area of the Santa Monica mountains to connect with the Ventura basin (Yerkes, et al., 1965; Slatt, et al., 1988, 1993). The depositional basin resembled present-day offshore basins in the continental borderland. These small, deep, basins are separated by sills produced by deformation along a series of fault zones parallel to the margins of the Pacific and North American plates. The basins step progressively outward and downward to the oceanic crust (Gorsline and Emery, 1959; Slatt et al., 1993).

The depositional Los Angeles basin has been divided into four structural blocks (Yerkes et al., 1965; Mayer, 1987, 1991), as shown on Figure 3. The contacts between blocks are major zones of faulting or flexure in the basement rocks. The northwestern block, north of the Santa Monica-Raymond Hill fault system, is part of the Transverse ranges (Wright, 1991). The southwestern block is located southwest of the Newport-Inglewood fault system. The portion of the southwestern block between the Newport-Inglewood fault system and the Palos Verdes uplift is called the western shelf (Wright, 1991), while the uplifted area west of the Palos Verdes fault comprises the sill for the depositional basin (Wright, 1987a). The central block, between the Newport-Inglewood and Whittier-Elsinore fault systems, provided a narrow deep depocenter known as the central trough. The northeastern block is located northeast of the Whittier-Elsinore fault system. Table 1 lists all oil and gas fields in the Los Angeles basin, with field discovery date, abandonment status, and the structural block(s) on which each field is located.

Pre-Miocene water depths are inferred to have been relatively shallow, based on alternating sequences of nonmarine and marine clastic facies (Mayer, 1987; Blake, 1991). The Neogene (Miocene and Pliocene) development of the depositional Los Angeles basin commenced during early Miocene time (Yerkes, et al., 1965; Beyer, 1988; Redin, 1991). Major middle Miocene deformation resulted in uplift and erosion of the inner borderland and western shelf; events included major block faulting and volcanism, with the Topanga group providing the ensuing sedimentary record. The Newport-Inglewood fault system displays evidence of deformation since at least middle Miocene time. The pre-Neogene history of the Newport-Inglewood fault system has been obscured by Paleogene (Paleocene, Eocene, Oligocene) terrane accretion. The Anaheim nose (east-central part of the central block) is a middle Miocene fault block, most of which is unconformably covered by sedimentary and volcanic rocks of the Topanga group. This feature was high during late Miocene time; thus, Mohnian- and Delmontian-stage (late Miocene to early Pliocene) strata are missing over the crest. The Anaheim nose was buried during middle Pliocene time, as recorded by progressive onlap of lower, middle and upper Repetto (early Pliocene, Repettian-stage) strata. The Palos Verdes hills display evidence of slow uplift beginning in late middle Miocene time (Wright, 1991).

The present form and structural relief of the depositional Los Angeles basin were established during late Miocene time when subsidence accelerated faster than deposition, resulting in a deep marine basin (Yerkes, et al., 1965; Campbell and Yerkes, 1976; Clarke, 1987; Mayer, 1987). Water depth in the basin was deepest (about 6000 to 8000 feet, or lower bathyal to abyssal depths) during late Miocene and early Pliocene time, when most of the area consisted of marine slope-to-basin environments (Conrey, 1959, 1967; Henry, 1987; Redin, 1991). At the close of the Miocene, the Los Angeles embayment had reached its greatest extent; it was bordered on its northeastern margin by hills that would later become the San Gabriel mountains, and the water surface was broken only by a shoal or island at the site of the present-day Anaheim nose (Yerkes, et al., 1965).

From early Pliocene to Pleistocene time, the basin continued to subside due to sediment loading, but tectonic subsidence had ceased (Mayer, 1987). The marginal areas of the basin began to rise during early Pliocene time, which contributed a rapid pulse of sedimentation that began to fill the basin so that the area of deposition diminished (Conrey, 1959, 1967; Yerkes, et al., 1965; Henry, 1987; Mayer, 1987). The Santa Monica mountains were uplifted in early Pliocene time along the Santa Monica-Raymond Hill fault system and have not since been submerged (Yerkes, et al., 1965). This uplift caused the marine connection between the San Fernando valley (northwestern block) and the main depositional Los Angeles basin (southwestern, central and northeastern blocks) to narrow to the zone between the eastern end of the Santa Monica mountains and the Verdugo mountains-San Rafael hills, which were also emergent. The small central trough of the San

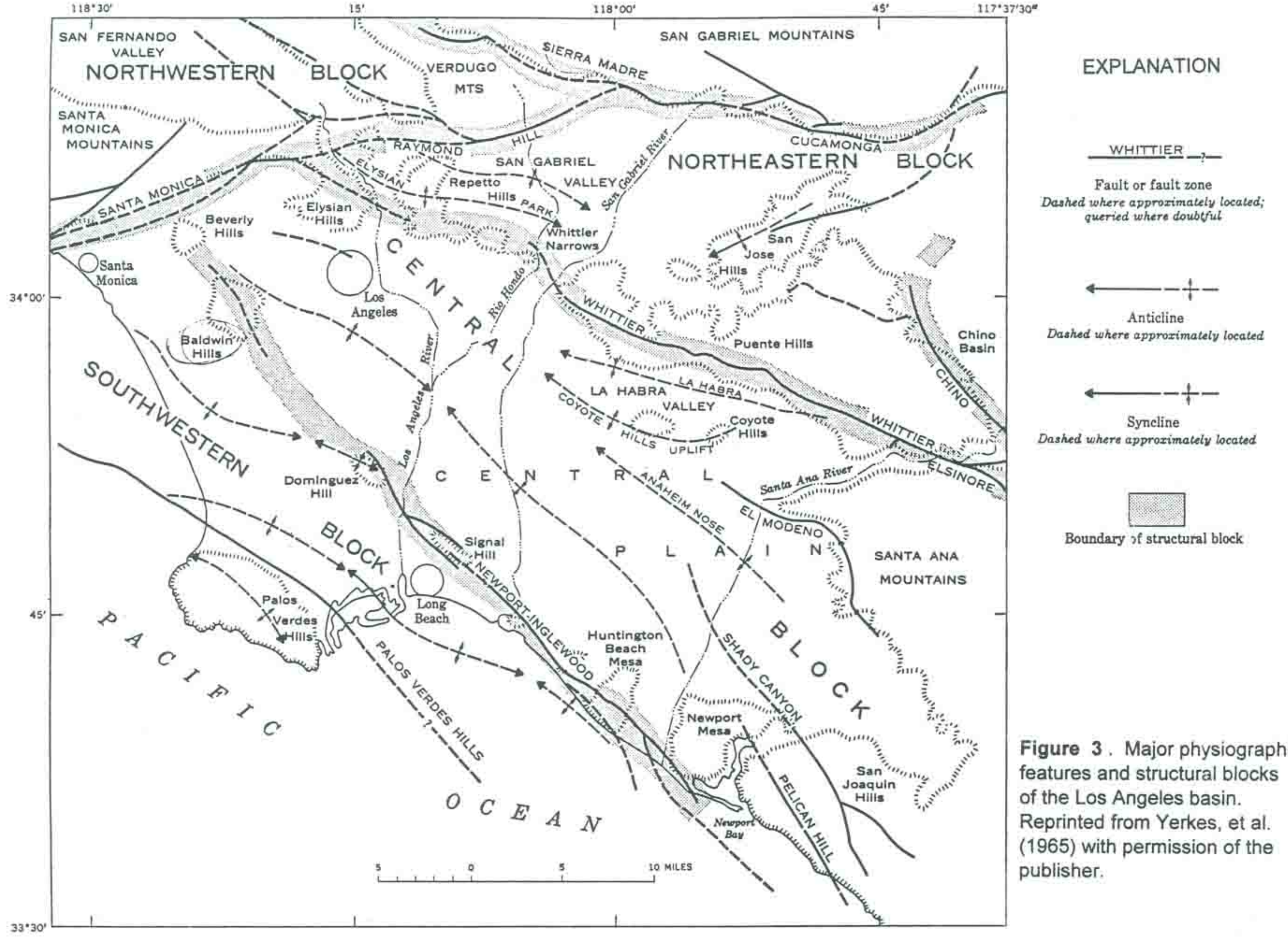


Figure 3. Major physiographic features and structural blocks of the Los Angeles basin. Reprinted from Yerkes, et al. (1965) with permission of the publisher.

FIELD NAME	DISCOVERY YEAR	STRUCTURAL BLOCK
Alondra	1946	Southwest
Anaheim	1951 (abandoned)	Central
Bandini	1953	Central
Belmont Offshore	1947	Southwest
Beta	1976	Southwest
Beverly Hills	1900	Central
Boyle Heights	1955 (abandoned)	Central
Brea-Olinda	1880	Northeast, Central
Buena Park, East	1942 (abandoned)	Central
Buena Park, West	1944 (abandoned)	Central
Cheviot Hills	1958	Central
Chino-Soquel	1902	Northeast
Coyote, East	1909	Central
Coyote, West	1909	Central
Dominguez	1923	Southwest, Central
El Segundo	1935	Southwest
Esperanza	1956	Central
Gaffey	1955 (abandoned)	Southwest
Howard Townsite	1947	Southwest, Central
Huntington Beach, Onshore	1920	Southwest, Central
Huntington Beach, Offshore	1933	Southwest
Hyperion	1944	Southwest, Central
Inglewood	1924	Southwest, Central
Kraemer	1918	Central
Kraemer, Northeast	1953 (abandoned)	Central
Kraemer, West	1956 (abandoned)	Central
La Mirada	1946 (abandoned)	Central
Lapworth	1935 (abandoned)	Northeast, Central
Las Cienegas	1961	Central
Lawndale	1928	Southwest
Leffingwell	1946 (abandoned)	Central
Long Beach	1921	Southwest
Long Beach Airport	1954	Central
Los Angeles City	Approx. 1890	Central
Los Angeles Downtown	1965	Central
Los Angeles, East	1946	Central

Table continues on p. .

FIELD NAME	DISCOVERY YEAR	STRUCTURAL BLOCK
Mahala	1921	Northeast and Chino Basin
Montebello	1917	Central
Newgate	1956	Central
Newport	1922	Southwest, Central
Newport, West	1953	Southwest
Olive	1953	Central
Playa del Rey	1929	Southwest
Potrero	1928	Southwest
Prado-Corona	1966	Chino Basin
Richfield	1919	Central
Rosecrans	1924	Southwest, Central
Rosecrans, East	1959	Central
Rosecrans, South	1939	Southwest, Central
Rowland	1931 (abandoned)	Northeast
Salt Lake	1902	Central
Salt Lake, South	1970	Central
Sansinena	1898	Central
San Vicente	1968	Central
Santa Fe Springs	1919	Central
Sawtelle	1965	Northwest
Seal Beach	1924	Southwest, Central
Sherman	1965 (abandoned)	Northwest
Sunset Beach	1954	Central
Talbert	1947 (abandoned)	Central
Torrance/Redondo	1922/1956	Southwest
Turnbull	1941 (abandoned)	Northeast
Union Station	1967	Central
Venice Beach	1966	Southwest
Walnut	1948	Northeast
Whittier	1896	Central
Whittier Heights, North	1944 (abandoned)	Northeast
Wilmington	1932	Southwest
Yorba Linda	1930	Central

Table 1. Oil and gas fields in the Los Angeles basin. Discovery year from California Division of Oil and Gas (1991). Refer to Figures 1 and 3 for location of fields and structural blocks.

Fernando valley was at slope-to-basin depths, but most of this sector consisted of intertidal to marine-shelf environments. The San Gabriel mountains, San Bernardino valley, Santa Ana mountains and San Joaquin hills were emergent areas. These areas were bordered by intertidal to marine-shelf environments along the slopes of the Santa Monica mountains, the San Gabriel valley, Puente hills, western slope of the Santa Ana mountains and San Joaquin hills. The area of the Palos Verdes hills uplift was also at intertidal to marine-shelf depth (Henry, 1987).

The margins of the depositional Los Angeles basin displayed erosional unconformities, rapid lithofacies changes and local faulting with increasing frequency in successively younger Pliocene strata (Beyer, 1988). The marine connection between the area of the San Fernando valley and the main depositional Los Angeles basin was eliminated; the central San Fernando valley consisted of shallow-marine environments. By late Pliocene time, only the central trough in the central block remained at marine slope-to-basin depths. The trough was rimmed by intertidal to marine-shelf environments which extended to the emergent areas of the Santa Monica mountains, San Gabriel valley, Puente hills, Santa Ana mountains and San Joaquin hills. The area of the Palos Verdes hills was also emergent (Conrey, 1959, 1967; Yerkes et al., 1965; Henry, 1987; Mayer, 1987; Wright, 1991). The Wilmington structure was partially emergent during late Pliocene time, which resulted in removal of lower to middle Pico and upper Repettian-stage strata, causing the top of the structure to be truncated by an almost flat erosional surface (Mayuga, 1968, 1970).

During Pleistocene time, all of the marine portion of the depositional Los Angeles basin consisted of intertidal to marine-shelf environments, including the Palos Verdes uplift (Yerkes, et al., 1965; Henry, 1987). The Wilmington structure was submerged and horizontal layers of younger strata were deposited over the erosional surface (Mayuga, 1968, 1970). All of the northwestern block and most of the northeastern block, with the exception of the Whittier Narrows area, was emergent, as was the expanded region of the Santa Ana mountains and the San Joaquin hills (Yerkes, et al., 1965; Henry, 1987). Pleistocene marine strata grade upward into nonmarine Pleistocene and Holocene (last 11,000 years) alluvium as the depositional basin filled to the present-day physiographic basin. Holocene deformation includes uplift in the Palos Verdes hills, along the Newport-Inglewood fault system, along the Santa Monica-Raymond Hill and Whittier-Elsinore fault systems and in the Santa Ana mountains and San Joaquin hills (Wright, 1991).

Early Field Discovery History

The discovery well for the first commercial production of oil and gas in the Los Angeles basin was drilled in 1880 in the "Puente field," which is now in the northwestern part of Brea-Olinda field (refer to Figure 1 and Table 1) (Durham and Yerkes, 1965; California Division of Oil and Gas, 1991). The "Puente field" and others discovered prior to 1901 in the area of the Puente hills were found by drilling near tar seeps occurring along the Whittier fault zone (Durham and Yerkes, 1964). Tar seeps were noted in the vicinity of present-day MacArthur (formerly Westlake) park as early as 1769 in the log of a Spanish overland expedition led by Don Gaspar de Portola (Crowder, 1961; Wright, 1987b). At one of these seeps a well was dug by hand in 1857 which was locally known as the Dryden well. Minor amounts of tar (or "brea") were produced from this well and from other seeps, and sold to the City of Los Angeles during the following 30 to 35 years. Around 1890, the Maltman Oil Company drilled nine wells in the Maltman tract and 12 wells in the Ruhland tract near the tar seeps proximal to MacArthur park. Production on pump was 2 BOPD per well of 12E API. In 1892, Doheny and Cannon completed a well in the "Second Street Park oil field" for 7 BOPD of 14E API, which became the central area of Los Angeles City field (Crowder, 1961).

During the first three decades of the 1900s, the study of surface geology dominated the search for oil; nearly all the structural features having surface expression in the Los Angeles basin were tested by the early 1930s (Durham and Yerkes, 1964). In 1932, Ranger Petroleum drilled the Watson No. 2 at Wilmington which produced on pump 150 BOPD of 14E API from the Ranger zone. The well was located in the extreme north-central portion of the field, and was assumed to be an extension of Torrance field (Thomas, 1957; Mayuga, 1968; Wright, 1987b). Geophysical and other subsurface methods were introduced into oil exploration during the 1930s (Durham and Yerkes, 1964). Based on the results of a seismic survey in 1936, General Petroleum Corporation (now Mobil Oil Corporation) drilled the Terminal No. 1, which tested the entire section and penetrated schist basement. The completion of this well at 1350 BOPD of 20.5E API (Upper Terminal zone) initiated an intensive drilling campaign southeast toward the Long Beach harbor district (Mayuga, 1968).

The Terminal No. 1 was carefully cored and tested, resulting in the discovery of the "Tar," Terminal and Ford zones (Thomas, 1957). By 1942, approximately 1000 wells were producing from the "Tar," Ranger, Upper and Lower Terminal and Ford zones. In 1942, Union Pacific Railroad Company discovered the Union Pacific zone in the interval between the Terminal and Ford zones. In 1944, the company drilled the Union Pacific No. 237 well, which discovered the "237" zone, between the base of the Ford zone and schist basement (Thomas, 1957). The oldest rocks in the field are the Jurassic to lower Cretaceous Catalina schist (Meyer, 1987) and the overlying basal conglomerate, which consists of rounded fragments of schist and volcanic rocks. The zone varies in thickness from a few inches to 30 to 40 feet. The "Basement zone" (comprised by conglomerate and schist) is productive where the schist is fractured and weathered. The areal extent is limited, with rapid production decline (Mayuga, 1968).

Production Trends

It is common for oil fields in the Los Angeles basin to occur on anticlines and upturned stratigraphic traps aligned over northwest-trending basement faults or over basement highs associated with these fault systems (Yeats and Beall, 1991). The Newport-Inglewood fault system is expressed at the surface as a series of aligned anticlines within which numerous discoveries have been made, ranging from Inglewood field near the northwest end of the system to West Newport in the southeastern portion of the Los Angeles basin (Figures 1 and 3).

To the west, the Redondo/Torrance and Wilmington/Belmont Offshore oil fields occur on a northwest-trending, gently-folded, asymmetrical anticline (Mayuga, 1968) underlain by a pre-existing basement high composed of Catalina schist (Clarke, 1987). Torrance oil field is separated from Wilmington by a low saddle (Mayuga, 1968). The basement high rises to about 600 feet below mean sea level (bmsl) under fault blocks II and III (Figure 2), drops to greater than 10,000 feet bmsl under the Long Beach unit (east Wilmington) and descends to greater than 16,000 feet bmsl under Huntington Beach Offshore (Clarke, 1987). There is a low nonproductive saddle separating Wilmington from Huntington Beach Offshore (Mayuga, 1968). The entire structure and associated faulting appear to be related to movement on the Newport-Inglewood fault system and the Palos Verdes fault to the southwest (Clarke, 1987; Yeats and Beall, 1991). Beta field is located east of, and adjacent to, the Palos Verdes fault, on the continental shelf (Yeats and Beall, 1991) about nine miles southwest of Huntington Beach (Wright, 1987b).

A similar group of northwest-trending oil fields overlies a basement high known as the schist ridge. This group of fields extends from Venice Beach and Playa del Rey in the northwest, through Hyperion, El Segundo, Lawndale and Alondra to merge with the

Newport-Inglewood fault system at Dominguez (Clarke, 1987; Yeats and Beall, 1991). A basal sand to conglomeratic unit was deposited on the erosional schist surface of moderate relief, locally filling valleys. Oil in the schist ridge is usually found in the basal conglomerate and underlying weathered, fractured schist, with the exception of Playa del Rey, which also produces oil from Repettian strata. El Segundo additionally produces gas in the upper part of the stratigraphic section (Beyer, 1988; Yeats and Beall, 1991). Production at Dominguez follows the trend of other fields along the Newport-Inglewood fault system, which produce primarily from late Miocene to early Pliocene submarine-fan (turbidite) facies.

Oil fields along the northwestern margin of the Los Angeles basin range from Sawtelle, Cheviot Hills and Beverly Hills fields in the west to Los Angeles Downtown and Boyle Heights on the east (Beyer, 1988). These fields are related to the fold-and-thrust belts associated with north-south convergence between the Santa Monica mountains and the Los Angeles basin (Beyer, 1988; Yeats and Beall, 1991).

In the portion of the central block northeast of the central trough, there is a group of fields aligned along the eastern part of the northern shelf (Bandini, East Los Angeles, Montebello) and along the northwest-trending Whittier-Elsinore fault system, from Whittier in the northwest to Esperanza in the southeast. A group of minor fields consisting of Anaheim, Buena Park East and West, and La Mirada, is related to the Anaheim nose. This structural feature is a subsurface ridge which represents the northwest extension of the Santa Ana mountains (Beyer, 1988; Yeats and Beall, 1991). Santa Fe Springs and Richfield oil fields are related to the west/northwest-trending Coyote Hills uplift and its southeast flank (Beyer, 1988). The group of anticlines in this uplift is associated with movement on the Whittier-Elsinore fault system (Wright, 1987a).

In the northeastern block, ten large anticlines are exposed in the Puente hills between the Whittier and Chino faults. The structure of this area is dominated by northeastward- and eastward-trending faults that branch from, and are related to, the northwest-trending Whittier-Elsinore fault system (Durham and Yerkes, 1964). All the fields in the northeastern block are minor, from Lapworth in the northwest to Rowland in the southeast, to the easternmost group of fields (Chino-Soqueo, Mahala, Prado-Corona) which are related to the northwest-trending Chino fault and Chino basin (Beyer, 1988).

REGIONAL STRATIGRAPHY AND NOMENCLATURE

The fault systems bounding each of the four structural blocks (Figure 3) appear to have allowed each block to have a different subsidence history and a different basement configuration (Mayer, 1987); thus, the stratigraphy and nomenclature for the depositional Los Angeles basin is extremely complex. Mayer (1987) presents different columnar sections for the northwestern and northeastern blocks and several significantly different sections within both the central and southwestern blocks. Mayer's (1987) work is a simplificatin of the detailed correlation sections of Yerkes, et al. (1965) which depict different formation names for stratigraphically-equivalent units as well as numerous breaks due to unconformities. The distinctions are particularly evident between emergent areas (Santa Monica mountains, Palos Verdes hills, San Joaquin hills, Santa Ana mountains) on different structural blocks and by comparison to submergent areas now in the subsurface of the central and southwestern blocks. Blake (1991) has compiled tables of stratigraphic detail for each of the emergent areas and for the subsurface portion of the basin.

Biostratigraphic Subdivision and Correlation

Extensive correlation work by oil-industry and USGS geologists using outcrop and conventional subsurface data since the early days of petroleum production in the Los Angeles basin has revealed that the basin is filled with a monotonous succession of alternating sand, silt and shale bodies. There are no distinctive "marker beds" which can be recognized and correlated in the subsurface over any significant distance (Wright, 1987a). Commencing in the 1920s, micropaleontologists found that microscopic fauna, particularly benthic foraminifera (associated with the benthos, or ocean-bottom dwelling) could be used to define distinctive zones which eventually provided the basis for defining the major stratigraphic subdivisions of the middle Miocene to Pleistocene source beds and clastic reservoirs within the depositional Los Angeles basin (Wright, 1987a; Blake, 1991).

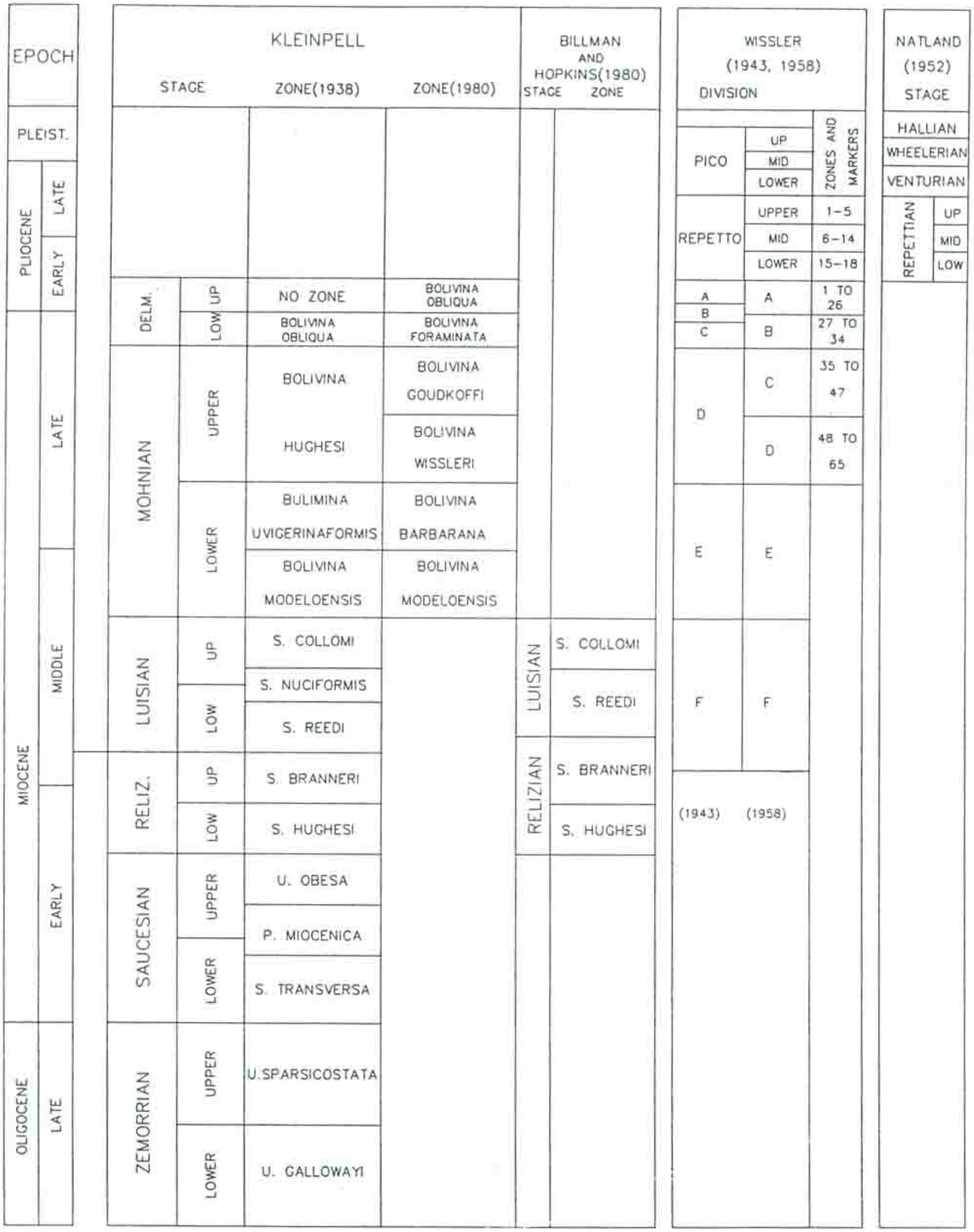
Although advances in other microfossil disciplines such as siliceous microfossils and calcareous nannoplankton provide potential for a more refined biostratigraphic framework to correlate lithologic units in the basin, benthic foraminiferal assemblages continue in use as the primary correlation tool for middle Miocene to Pleistocene strata (Blake, 1991). It is not possible to investigate the stratigraphic equivalents of any middle Miocene to Pleistocene unit throughout the depositional Los Angeles basin without defining the unit in terms of the foraminiferal stages of provincial California (Kleinpell, 1938), and the faunal divisions and foraminiferal zones devised by Wissler (1941, 1943, 1958), Natland (1952), and Natland and Rothwell (1954), as shown in Figures 4 and 5.

"Tar Zone" Stratigraphy and Biostratigraphy

The name Fernando formation was introduced in 1907 for Pliocene strata of the Ventura and Los Angeles basins (Eldridge and Arnold, 1907); in 1924, the designation was raised to the rank of group, into which were included the Pico and Saugus formations (Kew, 1924). After 1924, the entire Pliocene sequence of the depositional Los Angeles basin was assigned to the Pico formation (Blake, 1991). The terminology became so complex that the Society of Economic Paleontologists and Mineralogists (SEPM) appointed a committee to establish a uniform classification. In 1930, this committee proposed the name Repetto formation for the lower Pliocene and Pico formation for the upper Pliocene (Wissler, 1943; Blake, 1991). Durham and Yerkes (1964) have suggested that "Repetto" and "Pico" are not satisfactory as formational units because both are based on biostratigraphic rather than lithologic criteria, and that these terms should be replaced by lower and upper Fernando formation. Recent work in Wilmington field (Slatt, et al., 1993) used the 1924 terminology to designate the lower Pliocene as lower Pico and the upper Pliocene as upper Pico.

This paper follows the 1930 SEPM recommendation by limiting the Pico to the upper Pliocene and retaining "Repetto" for the lower Pliocene, but recognizes adjustments in formation boundaries which indicate that the Pico formation is now considered to be Plio-Pleistocene and the base of the "Repetto" is above the base of the Pliocene, as shown in Figures 4 and 5. This assignment of the terms Pico and "Repetto" is the standard terminology in proprietary and published oil industry reports and correlation sections (Wright, 1991). Substitution of the term lower Pico formation for "Repetto" risks significant confusion when using oil industry data where "Pico" is restricted to the Plio-Pleistocene unit. Typically, "Repetto" is designated by quotation marks to signify its informal nature, although this distinction is not usually also applied to the Pico.

Stratigraphic intervals, zones and subzones for producing units in Wilmington field are depicted in Figure 6. Faunal divisions and foraminiferal zones from paleontologic reports on core from the field (Warren and Newell, 1977) are consistent with the biostratigraphic framework for the depositional Los Angeles basin shown in Figures 4 and 5. Wireline-log character of the "Tar zone" and underlying Ranger zone as defined in "old



EPOCH		KLEINPELL STAGE		KLEINPELL ZONE(1938)	KLEINPELL ZONE(1980)	BILLMAN AND HOPKINS(1980) STAGE	BILLMAN AND HOPKINS(1980) ZONE	WISSLER (1943, 1958) DIVISION			NATLAND (1952) STAGE	
PLEIST.								PICO	UP	ZONES AND MARKERS	HALLIAN	
									MID		WHEELERIAN	
PLIOCENE	LATE								LOWER		VENTURIAN	
								REPETTO	UPPER	1–5	REPETTIAN	UP
	EARLY								MID	6–14		MID
									LOWER	15–18		LOW
MIOCENE	LATE	DELM.	UP	NO ZONE	BOLIVINA OBLIQUA			A	A	1 TO 26		
			LOW	BOLIVINA OBLIQUA	BOLIVINA FORAMINATA			B C	B	27 TO 34		
		MOHNIAN	UPPER	BOLIVINA HUGHESI	BOLIVINA GOUDKOFFI			D	C	35 TO 47		
					BOLIVINA WISSLERI				D	48 TO 65		
			LOWER	BULIMINA UVIGERINAFORMIS	BOLIVINA BARBARANA			E	E			
	MIDDLE			BOLIVINA MODELOENSIS	BOLIVINA MODELOENSIS							
		LUISIAN	UP	S. COLLOMI		LUISIAN	S. COLLOMI	F	F			
			LOW	S. NUCIFORMIS			S. REEDI					
				S. REEDI								
		RELIZ.	UP	S. BRANNERI		RELIZIAN	S. BRANNERI	(1943)	(1958)			
	EARLY		LOW	S. HUGHESI			S. HUGHESI					
		SAUCESIAN	UPPER	U. OBESA								
				P. MIOCENICA								
			LOWER	S. TRANSVERSA								
OLIGOCENE	LATE	ZEMORRIAN	UPPER	U.SPARSICOSTATA								
			LOWER	U. GALLOWAYI								

Figure 4. Correlation of benthic foraminiferal biostratigraphic zonations for the late Oligocene through Pleistocene of California. Zonations are calibrated to epochs as interpreted in 1991. "Tar zone" as defined in "old Wilmington" comprises most of the middle Repettian stage, excluding the uppermost and lowermost parts. Reprinted from Blake (1991) with permission of publisher.

Epoch	Stage	Faunal Division	Index Fossils	Foraminiferal Zone
Upper Pliocene	Venturian	Lower	Bulimina subacuminata Cushman and Stewart	
---?----?--- Lower Pliocene	Repettian	Upper	Cibicides mckannai Galloway and Wissler Plectofrondicularia californica Cushman and Stewart	1
				2
				3
				4
				5
		Middle	Karreriella milleri Natland	6
				7
				8
				9
				10
				11
				12
				13
				14
		Lower	Liebusella pliocenica (Natland)	15
				16
				17
				18
---?----?---	Delmontian	A	Rotalia garveyensis Natland	1 to 26
Upper Miocene		B	Bulimina sp. (large, crushed) - rare occurrence -	27 to 34
	Mohnian	C	Bulimina sp. (large, crushed) - abundant occurrence - Gyroidina rotundimargo R.E. & K.C. Stewart	35 to 47
		D	Bolivina hughesi Cushman Cassidulinella renulinaformis (Natland)	48 to 65
		E	Bulimina uvigerinaformis Cushman and Kleinpell Baggina californica Cushman	

Figure 5. Chart modified from Wissler (1941, 1943, 1958) , Natland and Rothwell (1954), and Conrey (1959, 1967).

EPOCH (STAGE)	FORMATION	ZONE	SUBZONES	FAUNAL DIVISION FORAM ZONE
Pleistocene	San Pedro			
Upper Pliocene	Pico		JF, KF, L	
----?----?----?----?---	"Repetto"		AO, BP, Q, R, R_1	
Lower Pliocene				Top mid.Repet. = Zone 6-1
(Repettian)		Tar	S, S_1, S_2, T	T = Zone 7-1
			D_U, D_1, D_2	D_U = Zone 10-1
			F_1, F_O	F_O = Zone 12-1
		Upper	F, F_2, F_3, F_4, H	
		Ranger	X, X_1, X_2, X_3	
(Delmontian)	Puente	Lower	G, G_1, G_2, G_4, G_5	G = Top Delmontian/Div. A
Lower Pliocene		Ranger	U_2, L_1, L_2, L_3	
		Upper	HX-series	
----?----?----?----?---		Terminal	J, Y, Y_2, Y_3, K, Z	
Upper Miocene			W, A, A_1, A_2	W = Top Division B
(Delmontian)		Lower	AA, AB, AC	
(Mohnian)		Terminal	AD, AD_1	AD approx. = Top Mohnian/
Upper Miocene				Division C
		Union	AE, AF, AI, AK	
		Pacific	AL_1, AM	
		Ford	AO, AR, AR_1	AR approx. = Top Div.D
			AU, AU_2, AV, AX	
			AY, AY_1, AZ	
		237	BA, BB, BC	
Middle Miocene	Topanga Group			
Jurassic to Lower	Catalina Schist	Basement		
Cretaceous (?)				

Figure 6. Stratigraphic intervals, zones and subzones in Wilmington field; "Tar zone" as defined in "old Wilmington." Data for faunal divisions and foram zones from Warren and Newell (1977). Foram zones 6 to 14 comprise the middle Repettian stage, characterized by Karreriella milleri index fossil. Epoch (stage), formation, zone and subzones modified from Slatt, et al. (1993).

Wilmington" field are shown in Figure 7. For comparison, the same composite type log from subzone AO (Figure 6) above the "Tar zone" to subzone AX within the Ford zone is shown in Figure 8 as defined in "new Wilmington," east of the Daisy Avenue-Golden Avenue fault system. The two illustrations differ in assignment of subzone F_1/F_O to the base of the "Tar zone" west of the fault system and to the top of the Ranger zone east of the fault system. Subzones shown on Figure 7 to the left of the wireline-log trace are Long Beach Harbor Department (LBHD) markers and to the right are Richfield Oil Company markers. Figure 8 omits the Richfield markers, which are essentially the same as the LBHD markers, but with more subzone designations.

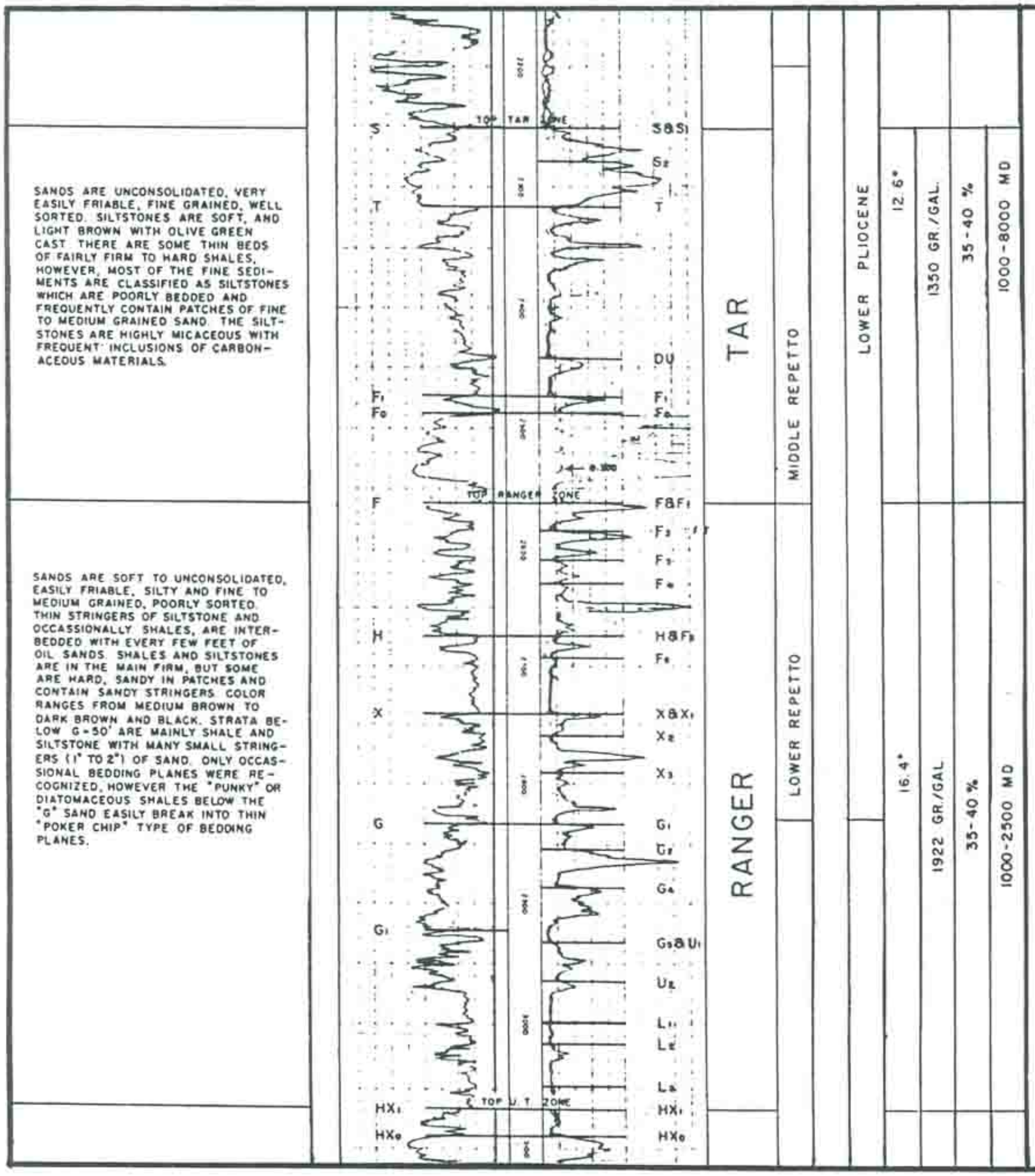
"Tar zone" sand bodies exhibit many depositional irregularities with significant lateral changes in lithology for some horizons. Examples are interval D_1-D_2 (below D_U) which changes character from a thick sand (west) to a shale body (east), and interval F_1/F_O-F which is shaly to the west, but a major sand body to the east, where it is developed with the underlying Ranger zone (Mayuga, 1968). "Tar zone" sand bodies are generally unconsolidated with an average porosity range of 30% to 40% and permeability range from 500 to 8000 millidarcies (weighted average of 1000 millidarcies). The zone averages 250 to 400 feet in thickness with oil gravity ranging from 12E to 15E API (Mayuga, 1968).

METHODS

The "Tar zone" was specifically defined for this paper as in "old Wilmington" to extend from Wilmington markers S through F_1/F_O (Figure 6). This interval was then identified as Repettian stage (early Pliocene), middle faunal division, characterized by Karreriella milleri index fossil, tentatively extending from foraminiferal zones 6 through 14 (Figure 5). Detailed review of all available cross-sections, correlation charts, type logs and paleontologic reports (Mayuga, 1955, 1959; McClellan, 1957; Hughes, 1964; Hunter, 1966; Warren and Newell, 1977; undated City of Long Beach drawings, charts, and a confidential paleontologic report) in City of Long Beach files and a correlation chart (Richfield Oil Corporation, 1939) obtained from Tidelands Oil Production Company, indicated that the "Tar zone" does not encompass the entire middle Repettian stage. Subzone S commences between foraminiferal zones 6 and 7; subzone F_O terminates below zone 12 but above zone 14 (base middle Repettian). The "Tar zone" was therefore defined as middle Repettian stage, excluding the uppermost and lowermost portions.

Currently existing literature and correlation sections are primarily based on the concurrence of Repettian stage with "Repetto" formation; thus, sections defining the middle "Repetto" formation, or where the middle "Repetto" can be inferred, can be used to identify the middle Repettian stage in the subsurface Los Angeles basin. Relatively recent published regional Los Angeles basin correlation sections which depict specific wells with wireline-log trace were relied on to provide the basic framework for this study (Henry, 1987; West, et al., 1987; West, et al., 1988; West and Reddin, 1990, 1991). For each field, these sections were compared to the type log and structural illustrations from the map and data sheets published by the California Division of Oil and Gas (DOG, 1991).

API gravity from the DOG (1991) field data sheets was used to identify the specific producing zone depicted in the stratigraphic sections of Yeats and Beall (1991), which show a combination of foraminiferal stages (Luisian, Mohnian, Delmontian), sometimes with faunal division (Divisions A, B, C, D, E), epoch (middle Miocene), lithology (schist, schist breccia or conglomerate, volcanics, igneous designation), formation (Sespe, Vaqueros, Topanga, "Repetto," Pico, San Pedro), fields, major faults, unconformities, and location of producing zones, usually with API gravity. Yeats and Beall (1991) use benthic microfaunal zone boundaries as though they marked time lines. Benthic zones are strongly



SANDS ARE UNCONSOLIDATED, VERY EASILY FRIABLE, FINE GRAINED, WELL SORTED. SILTSTONES ARE SOFT, AND LIGHT BROWN WITH OLIVE GREEN CAST. THERE ARE SOME THIN BEDS OF FAIRLY FIRM TO HARD SHALES, HOWEVER, MOST OF THE FINE SEDIMENTS ARE CLASSIFIED AS SILTSTONES WHICH ARE POORLY BEDDED AND FREQUENTLY CONTAIN PATCHES OF FINE TO MEDIUM GRAINED SAND. THE SILTSTONES ARE HIGHLY MICACEOUS WITH FREQUENT INCLUSIONS OF CARBONACEOUS MATERIALS.

SANDS ARE SOFT TO UNCONSOLIDATED, EASILY FRIABLE, SILTY AND FINE TO MEDIUM GRAINED, POORLY SORTED. THIN STRINGERS OF SILTSTONE AND OCCASSIONALLY SHALES, ARE INTERBEDDED WITH EVERY FEW FEET OF OIL SANDS. SHALES AND SILTSTONES ARE IN THE MAIN FIRM, BUT SOME ARE HARD, SANDY IN PATCHES AND CONTAIN SANDY STRINGERS. COLOR RANGES FROM MEDIUM BROWN TO DARK BROWN AND BLACK. STRATA BELOW G-50' ARE MAINLY SHALE AND SILTSTONE WITH MANY SMALL STRINGERS (1" TO 2") OF SAND. ONLY OCCASSIONAL BEDDING PLANES WERE RECOGNIZED, HOWEVER THE "PUNKY" OR DIATOMACEOUS SHALES BELOW THE "G" SAND EASILY BREAK INTO THIN "POKER CHIP" TYPE OF BEDDING PLANES.

Figure 7. "Tar zone" as defined in "old Wilmington" west of Daisy Avenue fault. This is the same composite type log as shown in Figure 8, but F_1/F_O units are assigned to the "Tar zone." The underlying Ranger zone commences with unit F. Base of the "Tar zone" (base of F_O) is near the base of the middle "Repetto" formation, which is approximately equivalent to the middle Repettian stage. Illustration reproduced from a portion of Long Beach Harbor Dept. Drawing F-150, City of Long Beach, Dept. of Oil Properties.

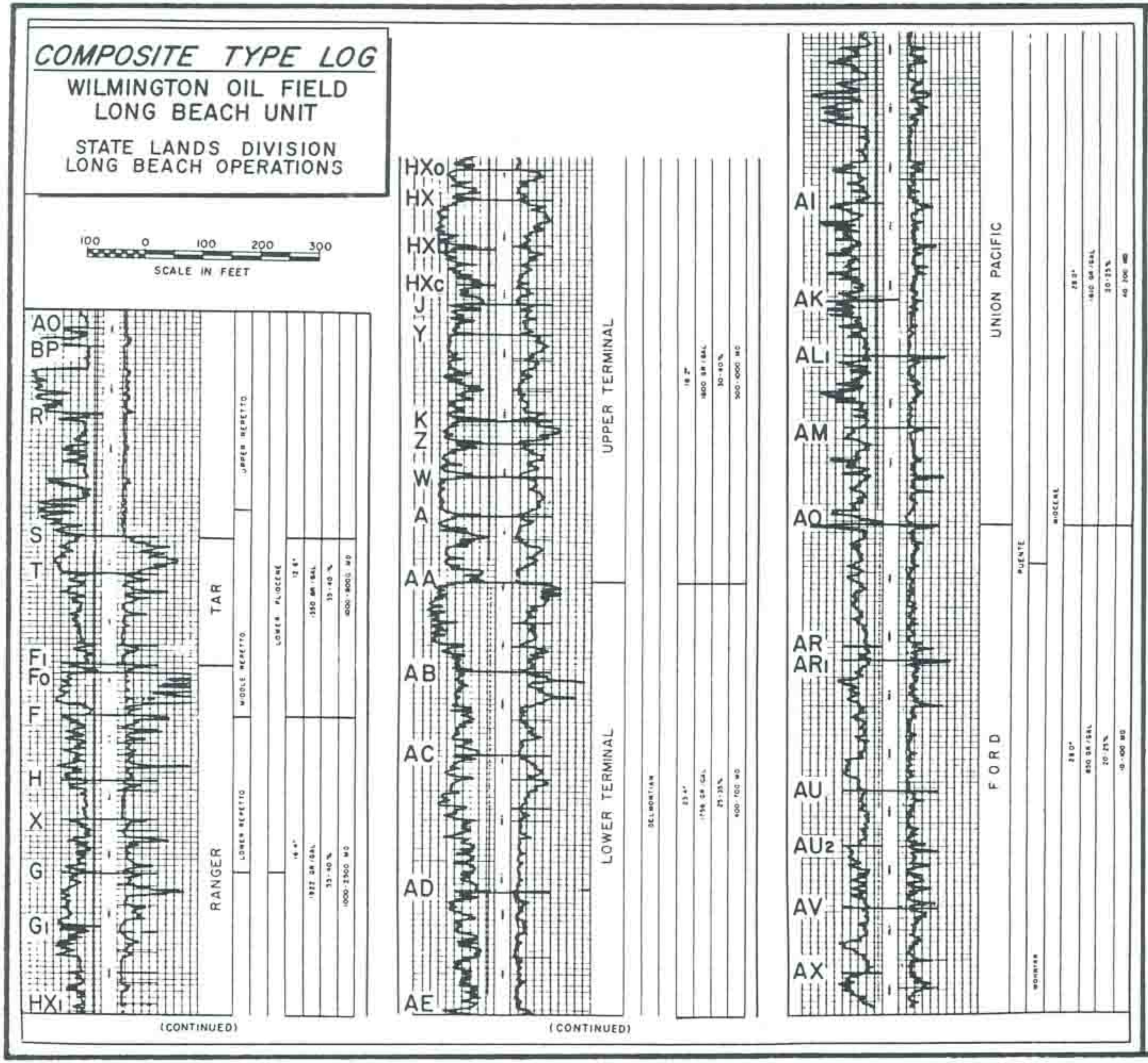


Figure 8. "Tar zone" as defined in "new Wilmington" east of Daisy Avenue fault. F_1/F_O units are assigned to the underlying Ranger zone. Drawing reproduced from City of Long Beach, Dept. of Oil Properties.

influenced by water depth and thus are actually time-transgressive; however, for the subsurface Los Angeles basin, most of the critical correlations are within the same environment (basin plain) and were not considered to significantly affect the analysis (Yeats and Beall, 1991). The "Repetto" generally is separated into lower, middle and upper units, which can be treated as Repettian stage; lower, middle and upper faunal division. For more detailed study, each well used for these sections is numbered and listed in the appendix to the Yeats and Beall (1991) paper.

Numerous cross-sections for areas and individual fields from Wright (1991) also depict the location of producing zones within the section and generally delineate lower, middle and upper "Repetto" while noting that the usage of these units as virtually synonymous with lower, middle and upper Repettian stage follows the opinion of Blake (1991). Wells shown in Wright's (1991) cross-sections are identified in his appendix 2. The basic correlation framework described above was supplemented where necessary with detailed lithologic and wireline log correlation sections from Conrey (1959, 1967), all of which distinguish between lower, middle and upper "Repetto," and with individual field references (Cordova, 1963; Durham and Yerkes, 1964; Loken, 1964; Gaede, 1964, 1965; Olson, 1974, 1977; Castle and Yerkes, 1976; Samuelian, 1984; Schweller, et al., 1988; Gidman, et al., 1993; Hesson, 1993).

DEPOSITIONAL SETTING

The lower sequence of Pliocene rocks is extensive in the subsurface of the depositional Los Angeles basin in the central and southwestern blocks. The dominant rock is arkosic sandstone, which is coarser to the northeast and finer in the southwest portion of the basin. The central block displays the greatest thickness of sediment and the most abundant sandstone bodies. Interbedded units of micaceous siltstone and sandy shale decrease in grain size and increase in organic content to the west and southwest (seaward). Conglomerate and pebbly sandstone predominate in the northeast and north-central portions of the central block (Conrey, 1959, 1967; Yerkes et al., 1965). Conrey (1959, 1967) also mapped areal variations in the composition of light minerals, heavy minerals and rock fragments.

Lithofacies and thickness relations of lower Pliocene rocks are depicted in Figure 9. Thickness isopach contours by Yerkes et al. (1965) are superimposed on lithofacies (percent sandstone and conglomerate) from Conrey (1958). Lithofacies in Figure 9 is a simplified version of the detailed maps prepared by Conrey (1959, 1967) separately for the lower, middle and upper divisions of the lower Pliocene. Figure 9 is generally similar to the separate map for the middle-lower Pliocene; thus, it provides a reasonable representation of lithofacies for the subsurface Los Angeles basin during the time period of deposition of the "Tar zone" in "old Wilmington" field and its stratigraphic equivalents in other parts of the basin. Conrey (1959, 1967) identified the submarine margins of the basin by the location of submarine fans, slump aprons, sedimentary pinchouts, angular unconformities, and the submarine sill (Palos Verdes uplift) which separated the deep portion of the basin from the open sea. Conrey concluded that many of the source areas (Santa Monica, San Gabriel and Santa Ana mountains; Puente, San Joaquin and Palos Verdes hills) were at various times during the lower Pliocene undergoing subaerial erosion (i.e., were emergent).

Repettian-Stage Submarine-Fan System

Migration pathways and reservoirs in the subsurface Los Angeles basin are dominated by Miocene and Pliocene turbidites (submarine-fan) and associated deep-water facies. Since these reservoir rocks directly overlie and are interbedded with

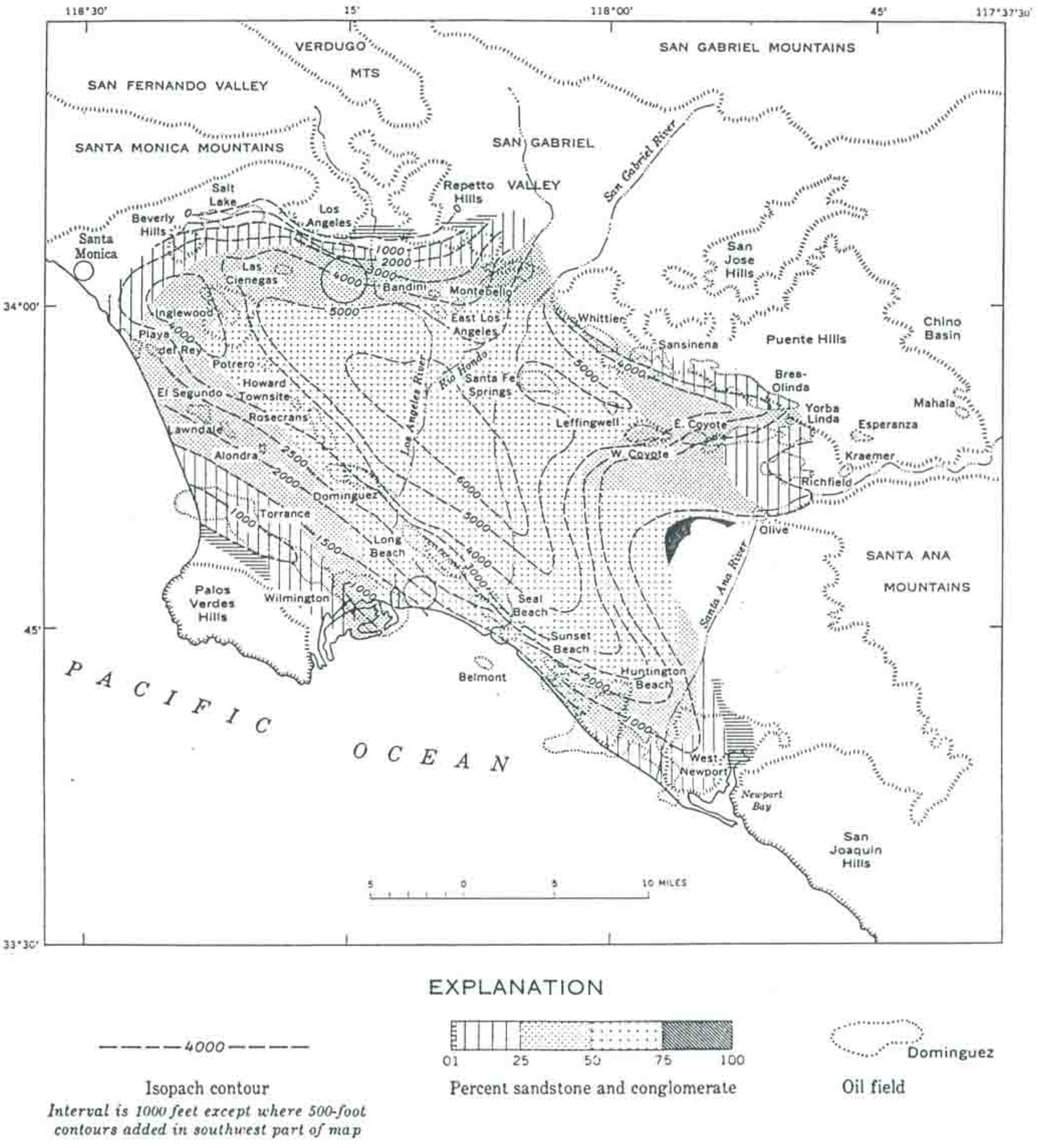


Figure 9. Lithofacies and thickness relations of lower Pliocene rocks of the Los Angeles basin. Reprinted from Yerkes et al. (1965) with permission of publisher. Isopachs by Yerkes et al. (1965) on lithofacies from Conrey (1958). Lithofacies is simplified version of Conrey (1959).

potential source rocks in many parts of the basin, the proximity facilitates communication from mature source to trap (Biddle, 1991; Redin, 1991; Yeats and Beall, 1991). Redin (1991) developed a series of submarine-fan facies models for the Los Angeles basin during Mohnian-, Delmontian-, and Repettian-stage deposition based on Normark (1978) as adjusted for the physiographic characteristics of the basin, and on Walker and Mutti (1973) for generalized facies descriptions.

Redin's (1991) model for all of the Repettian stage is compatible with Conrey's (1959, 1967) lithofacies map for the middle-lower Pliocene, and with the generalized Repettian-stage lithofacies map (Conrey, 1958) shown in Figure 9. A more detailed version of the facies descriptions for the Repettian-stage submarine-fan model is shown in Figure 10, which includes selected information from the original papers and from Walker (1978). The Repettian-stage submarine-fan facies map depicted in Figure 11 is adapted from Redin (1991) with the differentiation of upper fan overbank and shelf slope, distal turbidites, and submarine high designations into separate lithofacies symbols on the map for clarity. Direction of sediment transport is shown by the flow arrows on Figure 11.

Although slump aprons along the slopes provided material from sources in the Santa Monica mountains, Puente hills, San Joaquin hills, and Palos Verdes hills, the primary sources of coarse clastic material were the San Gabriel and Santa Ana submarine-canyon systems (Conrey, 1959, 1967; Redin, 1991), as indicated on Figure 11. The Repettian-stage middle to upper channelized-fan system is very sandy to conglomeratic; thus, hemipelagic and fine-grained distal facies are of less importance volumetrically than in the Mohnian and Delmontian submarine-fan models (Redin, 1991).

RESULTS AND DISCUSSION

Approximate stratigraphic equivalents of the "Tar zone" as defined in "old Wilmington" field are shown in Table 2 for every field in the depositional Los Angeles basin. The table indicates whether middle Repettian-stage strata are present, and if not, the cause of the absence. In some cases (Mahala, Prado-Corona) in the northeastern block, the fields are in shallow-water marine facies, so that a possible equivalent is not designated, not productive, and may not be differentiated. There are a number of fields where middle Repettian-stage strata are present, but there is no designated zone name because it is not productive. For every field where the middle Repettian is designated and productive, API gravity is shown for comparison to the "Tar zone" at "old Wilmington," which is 12E to 15E API. The location of each field (Figure 1) was compared to the Repettian-stage submarine-fan facies map (Figures 10 and 11) to determine the generalized marine depositional environment for the middle-Repettian stratigraphic equivalents (if present) to the "Tar zone" in each field (Table 2).

CONCLUSION

Table 2 can be used to identify all fields in the subsurface Los Angeles basin which have approximate stratigraphic equivalents to the "Tar zone" as defined in "old Wilmington" field. Similarity of depositional environment for each stratigraphic equivalent and of API gravity for those stratigraphic equivalents which are productive of hydrocarbons can be identified from Table 2 and from location maps for fields (Figure 1) and for Repettian-stage submarine-fan facies associations (Figures 10 and 11). The table can be used to direct the results of the U.S. DOE field demonstration program for the "Tar zone" in "old Wilmington" field to those oil and gas operators in the Los Angeles basin most likely to benefit from access to the technology-transfer network.

ACKNOWLEDGEMENTS

EXPLANATION

▒	MIDDLE TO UPPER CHANNELIZED FAN Dominantly pebble, cobble, and boulder conglomerate bodies with sandy matrix; or pebbly sandstone bodies. Beds may be massive or display fabric which is crudely stratified, imbricated, or shows preferential clast orientation. Sand/shale ratio commonly exceeds 10:1.
░	SUPRAFAN Massive, fine- to coarse-sand size, often amalgamated, sandstone bodies. Beds are commonly lenticular with scouring at the base; finely-alternating parallel lamination to crude subparallel stratification. Finer-grain bodies tend to grade up into a shaly division. Sand/shale ratio of 5:1 to over 10:1.
▤	UPPER FAN OVERBANK AND SHELF SLOPE Laminated mudstone alternating with very thin-bedded fine-grain sandstone bodies.
┄	DISTAL TURBIDITES Silt to fine sand with low sand/shale ratio of 1:1 or less; graded bedding is common. Biological activity (horizontal trails and burrows, vertical burrows) is commonly preserved. Bioturbation may totally disrupt bedding, resulting in massive siltstone.
▓	SUBMARINE HIGH Very thin-bedded silt to fine-grain sandstone bodies; or section missing due to erosion or non-deposition.
☰	HEMIPELAGIC SUBMARINE HIGH Predominantly silty or calcareous hemipelagic shale and marl; very dilute suspension deposits.

Figure 10. Explanation for Repettian-stage submarine-fan facies map shown in Figure 11. Lithofacies definitions modified after Walker and Mutti (1973), Normark (1978), Walker (1978), and Reddin (1991).

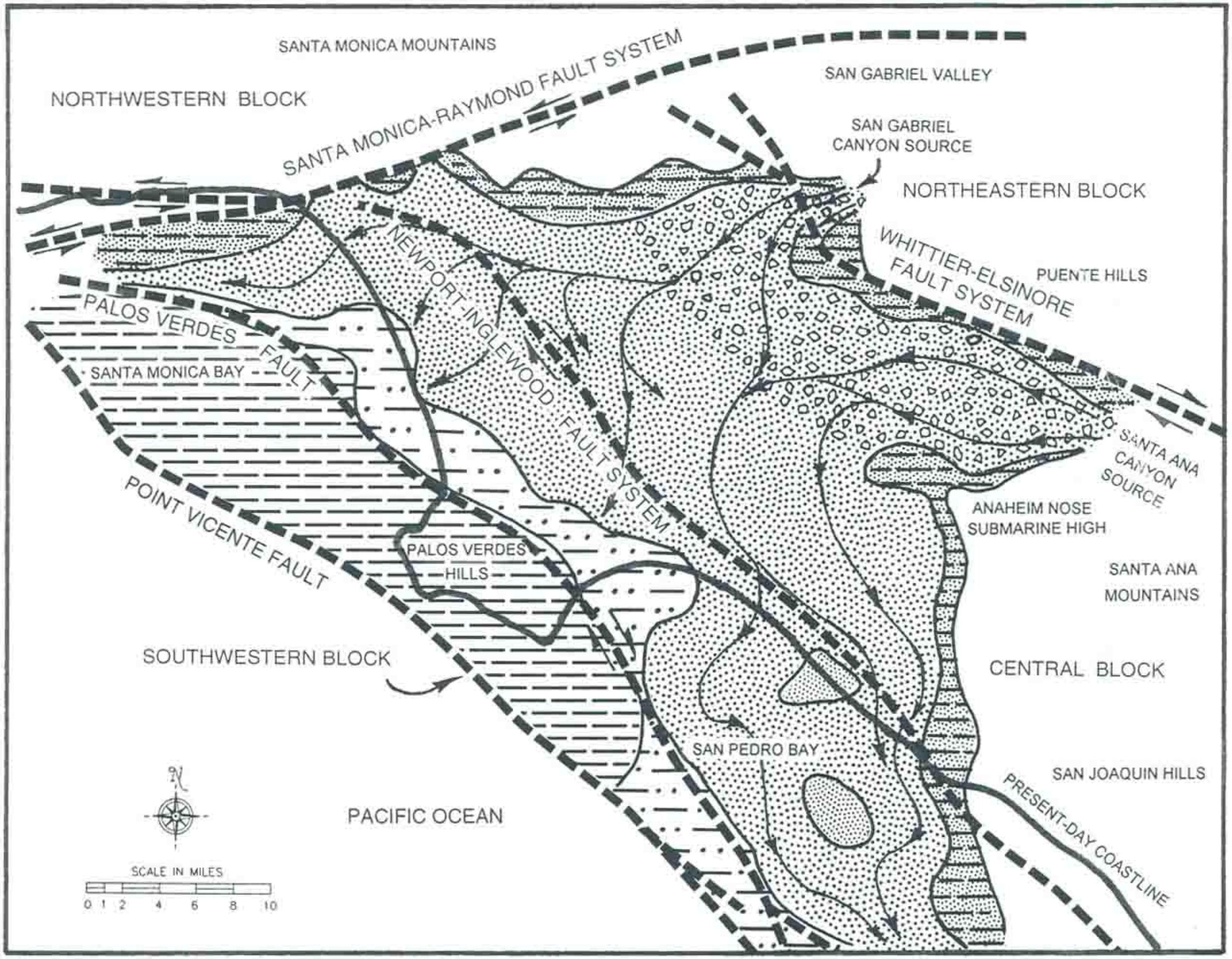


Figure 11. Present-day Repettian-stage submarine-fan facies map, Los Angeles basin. Refer to Figure 10 for explanation. Adapted from Redin (1991).

FIELD NAME	MIDDLE REPETTIAN	APPROX. STRAT. EQUIVALENT	API GRAVITY	GENERALIZED MARINE DEPOSITIONAL ENVIRON.
Wilmington	Present	"Tar zone": S through F_1/F_o	12°-15°	Distal turbidites (W,S) to suprafan with channels (E,N)
Alondra	Present	Not designated	Not prod.	Suprafan with channels
Anaheim	Uncon., Pico on Topanga	Not present	None	Not present
Bandini	Present	Nordstrom zone	40°	Mid to upper channelized fan
Belmont Offshore	Present	"Tar equivalent" F_1/F_o Ranger)	Not prod. 16°-20°	Suprafan with channels
Beta	Present	Not designated	Not prod.	Distal turbidites to suprafan with channels
Beverly Hills	Present, east area	"Repetto sands" (to R_4); Bedford	35°	Shelf slope to suprafan with channels
Boyle Heights	Present	Not designated	Not prod.	Shelf slope to suprafan with channels
Brea-Olinda	Present SW of Whittier flt.	"Tar zone" 1st Pliocene zone	Not prod. 15°-18°	Upper fan overbank and shelf slope; mid-upper channel. fan
Buena Park, East	Present	Spencer Cannon	21° 22°	Upper fan overbank and shelf slope; mid to upper channelized fan
Buena Park, West	Present	Heath	28°	Suprafan with channels
Cheviot Hills	Present	"Repetto sands"	22°	Shelf slope to suprafan with channels
Chino-Soquel	Miocene at surface	Not present	None	Not present
Coyote, East	Present	1st and 2nd Anaheim	16°-25°	Mid to upper channelized fan
Coyote, West	Present	Lower 99 zone 138 zone	29° 23°-28°	Mid to upper channelized fan
Dominguez	Present	3rd and 4th Callender	29°-33°	Suprafan with channels
El Segundo	Present	4200 ft; 4300 ft; 4400 ft; 4700 ft?	Gas zones 1000 BTU	Suprafan with channels
Esperanza	Miocene at surface	Not present	None	Not present
Gaffey	Present NE of Palos Verdes fault	Not designated	Not prod.	Hemipelagic submarine high to distal turbidites
Howard Townsite	Present	Not designated	Not prod.	Suprafan with channels
Huntington Beach, Onshore	Present	Middle Bolsa Lower Bolsa	11°-24° 11°-24°	Submarine high to suprafan with channels
Huntington Beach, Offshore	Present	"AA zone" may be equivalent to F_1/F_o	14.8°	Submarine high to suprafan with channels
Hyperion	Present	Est. 300 ft below to above "L" marker	Not prod.	Distal turbidites to suprafan with channels
Inglewood	Present	Upper and Lower Rubel	20°-35°	Suprafan with channels

Table continues on p. .

FIELD NAME	MIDDLE REPETTIAN	APPROX. STRAT. EQUIVALENT	API GRAVITY	GENERALIZED MARINE DEPOSITIONAL ENVIRON.
Kraemer	Miocene at surface	Not present	None	Not present
Kraemer, Northeast	Miocene at surface	Not present	None	Not present
Kraemer, West	Miocene at surface	Not present	None	Not present
La Mirada	Present	Not designated	Not prod.	Mid to upper channelized fan
Lapworth	Present	Not designated	Not prod.	Upper fan overbank and shelf slope
Las Cienegas	Present	Not designated	Not prod.	Suprafan with channels
Lawndale	Present	Not designated	Not prod.	Suprafan with channels
Leffingwell	Present	138 zone equivalent Upper Lewis	Not prod. 34°	Mid to upper channelized fan
Long Beach	Present	Middle Brown zone	18°-30°	Suprafan with channels
Long Beach Airport	Present	Middle Bown zone	Not prod.	Suprafan with channels
Los Angeles City	Miocene at surface	Not present	None	Not present
Los Angeles Downtown	Present	Not designated	Not prod.	Suprafan with channels
Los Angeles East	Present	Nordstrom (zone Bandini)	Not prod.	Mid to upper channelized fan
Mahala	Present?	Not designated	Not prod.	Shallow-water marine
Montebello	Present	2nd zone	25°	Mid to upper channelized fan
Newgate	Present	Nordstrom	Not prod.	Mid to upper channelized fan
Newport	Uncon., Pico on Puente	Not present	None	Not present
Newport, West	Present	Not designated	Not prod.	Shelf slope to suprafan with channels
Olive	Unconformity, Upper Repetto on Puente	Not present	None	Not present
Playa del Rey	Present	"Upper zone" (Venice area)	20°	Suprafan with channels
Potrero	Present	Pacific/Coffin zone (5200 ft; 5800 ft?)	44° (5200 ft);34°-48°	Suprafan with channels
Prado-Corona	Present?	Not designated	Not prod.	Shallow-water marine
Richfield	Present	"Tar sand"	12°-14°	Mid to upper channelized fan
Rosecrans	Present	Lower Maxwell Hoge	29°-40° 32°-40°	Suprafan with channels
Rosecrans, East	Present	Not designated	Not prod.	Suprafan with channels
Rosecrans, South	Present	Not designated	Not prod.	Suprafan with channels
Rowland	Miocene at surface	Not present	None	Not present
Salt Lake	Present	"A zone"?	14°-18°	Shelf slope
Salt Lake, South	Present	Clifton C-30, C-35 C-40?	22°	Shelf slope

Table continues on p. .

FIELD NAME	MIDDLE REPETTIAN	APPROX. STRAT. EQUIVALENT	API GRAVITY	GENERALIZED MARINE DEPOSITIONAL ENVIRON.
Sansinena	Present	1st Whittier	17°	Upper fan overbank and shelf slope
San Vicente	Present	"Clifton sands"	25°	Shelf slope
Santa Fe Springs	Present	Lower Meyer Nordstrom	35° 35°	Mid to upper channelized fan
Sawtelle	Unconformity and faulting	Not present	None	Not present
Seal Beach	Present	San Gabriel?; Bixby Selover	20°-27° 21°-25° 24°-28°	Suprafan with channels
Sherman	Undiff. Pico and Repetto	Sherwood zone?	23°	Shallow-water marine
Sunset Beach	Present	Middle Bolsa Lower Bolsa	Not prod.	Suprafan with channels
Talbert	Present	Not designated	Not prod.	Suprafan with channels
Torrance/Redondo	Present	"Tar zone"	Not prod.	Distal turbidites
Turnbull	Present	Not designated	Not prod.	Upper fan overbank and shelf slope
Union Station	Present	Not designated	Not prod.	Shelf slope to suprafan channels
Venice Beach	Present?	Not designated	Not prod.	Suprafan with channels
Walnut	Basal Repetto and Miocene at surface	Not present	None	Not present
Whittier Heights,	At surface	Not designated	Not prod.	Upper fan overbank and shelf slope
Yorba Linda	Present	Main (Signet sand) Shell zone	13°-17° 13°-20°	Upper fan overbank and shelf slope; mid to upper channelized fan

Table 2. Approximate middle Repettian stratigraphic equivalents in the subsurface Los Angeles basin to the "Tar zone" in "old Wilmington" field, defined as S through F_1/F_O units. API gravity in most cases follows California Division of Oil and Gas publication TR12 (1991). Refer to Figures 10 and 11 for explanation and depiction of generalized facies and marine depositional environments of the Repettian stage, Los Angeles basin. Uncon. = unconformity; flt. = fault; undiff. = undifferentiated; est. = estimated; prod. = productive. Uncertain correlations are queried.

Acknowledgements are made to Dr. Iraj Ershagi, Professor of Petroleum Engineering at the University of Southern California, Los Angeles, California, for posing the problems researched herein, and for editing this paper. Phillip Scott Hara, Chief Production Engineer, and Christopher Phillips, Chief Geologist, Tidelands Oil Production Company in Long Beach, California, provided advice and a correlation chart prepared by Richfield Oil Corporation. Donald D. Clarke, Senior Geologist with the City of Long Beach, Department of Oil Properties, provided access to all available cross-sections, correlation charts, type logs, and paleontologic reports in the City of Long Beach files. Don Clarke and Michael J. Henry, Geologist with the City of Long Beach, reviewed with the author the planned approach to identifying "Tar zone" stratigraphic equivalents across the Los Angeles basin for compatibility with previous and on-going research in Wilmington field.

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FIELD NAME	DISCOVERY YEAR	STRUCTURAL BLOCK
Alondra	1946	Southwest
Anaheim	1951 (abandoned)	Central
Bandini	1953	Central
Belmont Offshore	1947	Southwest
Beta	1976	Southwest
Beverly Hills	1900	Central
Boyle Heights	1955 (abandoned)	Central
Brea-Olinda	1880	Northeast, Central
Buena Park, East	1942 (abandoned)	Central
Buena Park, West	1944 (abandoned)	Central
Cheviot Hills	1958	Central
Chino-Soquel	1902	Northeast
Coyote, East	1909	Central
Coyote, West	1909	Central
Dominguez	1923	Southwest, Central
El Segundo	1935	Southwest
Esperanza	1956	Central
Gaffey	1955 (abandoned)	Southwest
Howard Townsite	1947	Southwest, Central
Huntington Beach, Onshore	1920	Southwest, Central
Huntington Beach, Offshore	1933	Southwest
Hyperion	1944	Southwest, Central
Inglewood	1924	Southwest, Central
Kraemer	1918	Central
Kraemer, Northeast	1953 (abandoned)	Central
Kraemer, West	1956 (abandoned)	Central
La Mirada	1946 (abandoned)	Central
Lapworth	1935 (abandoned)	Northeast, Central
Las Cienegas	1961	Central
Lawndale	1928	Southwest
Leffingwell	1946 (abandoned)	Central
Long Beach	1921	Southwest
Long Beach Airport	1954	Central
Los Angeles City	Approx. 1890	Central
Los Angeles Downtown	1965	Central
Los Angeles, East	1946	Central

Table continues on p.   .

FIELD NAME	DISCOVERY YEAR	STRUCTURAL BLOCK
Mahala	1921	Northeast and Chino Basin
Montebello	1917	Central
Newgate	1956	Central
Newport	1922	Southwest, Central
Newport, West	1953	Southwest
Olive	1953	Central
Playa del Rey	1929	Southwest
Potrero	1928	Southwest
Prado-Corona	1966	Chino Basin
Richfield	1919	Central
Rosecrans	1924	Southwest, Central
Rosecrans, East	1959	Central
Rosecrans, South	1939	Southwest, Central
Rowland	1931 (abandoned)	Northeast
Salt Lake	1902	Central
Salt Lake, South	1970	Central
Sansinena	1898	Central
San Vicente	1968	Central
Santa Fe Springs	1919	Central
Sawtelle	1965	Northwest
Seal Beach	1924	Southwest, Central
Sherman	1965 (abandoned)	Northwest
Sunset Beach	1954	Central
Talbert	1947 (abandoned)	Central
Torrance/Redondo	1922/1956	Southwest
Turnbull	1941 (abandoned)	Northeast
Union Station	1967	Central
Venice Beach	1966	Southwest
Walnut	1948	Northeast
Whittier	1896	Central
Whittier Heights, North	1944 (abandoned)	Northeast
Wilmington	1932	Southwest
Yorba Linda	1930	Central

Table 1. Oil and gas fields in the Los Angeles basin. Discovery year from California Division of Oil and Gas (1991). Refer to Figures 1 and 3 for location of fields and structural blocks.