U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

PETROLEUM GEOLOGY OF THE SANTA MARIA BASIN ASSESSMENT PROVINCE, CALIFORNIA FOR THE 1987 NATIONAL ASSESSMENT OF UNDISCOVERED OIL AND GAS RESOURCES

by

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CONTENTS

INTRODUCTION

This report presents a summary of the geology used as a basis for the U.S. Geological Survey's 1987 assessment of undiscovered oil and gas resources in the Santa Maria Basin assessment province. The petroleum geology was taken for the most part from published sources, principally Crawford (1971) and California Division of Oil and Gas (1974).

The assessment was made on a baseline of discovered oil and gas resources (cumulative production plus proved reserves) from the Nehring data base as of 12/31/83 (NRG Associates, 1984) which includes only fields with resources exceeding 1 MMBOE (million barrels oil equivalent). The figures correspond to those in California Division of Oil and Gas (1984) which includes fields of all sizes. Reserve additions due to field development or new discoveries subsequently declared by the California Division of Oil and Gas were for assessment purposes regarded as undiscovered resources.

Total cumulative production in the assessment province through 1983 was 762 MMbbl (million barrels) oil, 53 MMbbl NGL (natural gas liquids), and 705 Bcf (billion cubic feet) gas; proved reserves totalled 165 MMbbl oil, 9 MMbbl NGL, and 107 Bcf gas (NRG Associates, 1984).

BASIN LOCATION

The Santa Maria Basin assessment province is located in central coastal California. As defined (Figure 1A), the province is bounded on the south approximately by the Santa Ynez fault, on the east by the Santa Barbara-Ventura County line, and on the west (offshore) by the western limit of state waters within 3 miles of shore from Jalama (at the south) nearly to Monterey (at the north). On the northeast, the assessment province is generally bounded by the Sur-Nacimiento fault but extends beyond that fault north of 36°N to include the approximate extent of exposed pre-Cretaceous metamorphic basement rocks.

Geologically speaking, the assessment province mainly represents the Tertiary onshore Santa Maria Basin, Pismo Basin ("Arroyo Grande district" in Figure 2), and Huasna Basin "Huasna district" in Figure 2). In addition, the assessment province also includes small unnamed Tertiary basins or basin fragments in the Coast Ranges west of the Sur-Nacimiento fault, a piece of the Tertiary Salinas Basin northeast of the Sur-Nacimiento fault in the area north of 36°N, a wedge along the southern boundary that is regarded by some as part of the Tertiary Santa Barbara-Ventura Basin, and slivers of the Tertiary Sur and offshore Santa Maria Basins in adjacent offshore state waters (Figure 2).

STRUCTURAL SETTING

Prevailing views of the formation of west coast Neogene basins are based on modifications of Atwater's (1970) and Atwater and Molnar's (1973) plate tectonic model for the west coast of North America. In this model, Neogene basins were formed at a triple junction (between the North American, Pacific, and Farallon Plates) that migrated north and south from the vicinity of southern California between 29 Ma and present (Figure 3). Various theories address the formation of basins within this setting (e.g. Blake and others, 1978) including a model for the formation of the Neogene Santa Maria geologic basin as a pull-apart basin during strike-slip tectonism (Hall, 1981b). Another theory about the Neogene Santa Maria geologic basin is that it formed as an area of thinned crust related to clockwise tectonic rotations of elongate crustal blocks bounded by more or less vertical faults (Figure 4; Hornafius, 1985, Hornafius and others, 1986).

The Miocene and younger structural style of the assessment province has generally been regarded as dominated by wrench tectonics and associated vertical strike-slip faulting (e.g., Howell and others, 1980; Figures 5, 6A). However, compressional tectonics and associated thrust and high-angle reverse faulting were more recently advocated as the dominant structural style in the development of adjacent offshore areas (Crouch and others, 1984; Figure 6B). Subsequent to the assessment, major anticlinal structures throughout the assessment province have been related to fault-bend and fault-propagation folds in a Pliocene and younger fold and thrust belt (Namson and Davis, 1990).

STRATIGRAPHY

The Santa Maria Basin assessment province is mainly included in the Sur-Obispo composite terrane of Vedder and others (1983), a composite of the San Simeon terrane and the Stanley Mountain terrane. Basement rocks in the San Simeon terrane consist of pre-Jurassic, Jurassic, and Cretaceous Franciscan melange (Figure 7), and basement rocks in the Stanley Mountain terrane consist of Coast Range ophiolite and upper Jurassic (?) and Cretaceous sedimentary rocks of the Espada or "Knoxville" Formation.

In most of the assessment area, an unconformity represents Late Cretaceous and most of Paleogene time (Vedder and others, 1983). Between this unconformity and the widespread predominantly fine-grained Miocene strata of the Miocene Monterey Formation (and/or Point Sal Formation), the stratigraphy varies from locality to locality. In the southernmost part of the assessment area (Figures 8D, 8E) is an Eocene-Oligocene sequence overlain locally by the Oligocene-Miocene Sespe Formation. Overlying the Sespe there, and overlying the Late Cretaceous-early Paleogene unconformity in the Huasna (Figure 8A) and Pismo (Figure 8B) geologic basins and in coastal areas to the north that are west of the Sur-Nacimiento fault, is a sequence that includes sandstones of the Oligocene-Miocene Vaqueros Formation and shale and sandstone of the early Miocene Rincon Shale. Overlying the Rincon Shale are volcaniclastic and sedimentary rocks of the lower-middle Miocene Obispo Tuff in areas north of the Santa Maria geologic basin (Figures 8A, 8B), and the Tranquillon Volcanics locally in the southern part of the assessment province (Figures 8D, 8E; Dibblee, 1950, 1966). Locally in the Santa Maria geologic basin, especially in the northwestern part of the basin, the Late Cretaceous-Paleogene unconformity is overlain by non-marine sandstones, conglomerates, and mudstones of the

Lospe Formation (Figure 8C). This unit, now dated as early Miocene in age (Stanley and others, 1991), was at the time of the assessment presumed to be uncertainly of late Oligocene or early Miocene age.

Overlying the Rincon Shale in the southernmost part of the assessment area (Figures 8D, 8E), the Obispo Tuff in areas north of the Santa Maria geologic basin (Figures 8A, 8B), the Lospe Formation locally within the Santa Maria geologic basin (Figure 8C), and Franciscan or Cretaceous sedimentary rocks within much of the Santa Maria geologic basin, are the predominantly fine-grained strata of the Miocene Point Sal and Monterey Formations. These strata consist mainly of bathyal clay-bearing siliceous-calcareous, calcareous-siliceous, and siliceous mudstones and shales derived from diatom and coccolith-foraminiferal oozes. Where sandstones are notably abundant in the lower part of these strata (as in the central part of the onshore Santa Maria basin) and by local custom in other areas (such as the Pismo and Huasna basins), the lower part of this sequence is locally included in the Point Sal Formation.

Overlying the Monterey Formation are sequences of marine sedimentary rocks generally representing deposition in comparatively shallow environments. In the Santa Maria geologic basin (Figure 8C; Lagoe, 1987), the Monterey Formation is overlain (in places disconformably or with slight to significant angularity) by outer neritic clayey-siliceous mudstones (uppermost Miocene and lower Pliocene Sisquoc Formation, as much as 5000 ft thick), clayey mudstones (Pliocene Foxen Mudstone), and shallow marine sandstone and conglomerate (upper Pliocene Careaga Sandstone). In the Pismo basin (Figure 8B), the Monterey Formation is not defined equivalently in that a thick sequence of upper Miocene siliceous mudstones and shales is locally included in the overlying Pismo Formation. The Pismo Formation also includes shallow marine sandstones and conglomerates of latest Miocene and Pliocene age (Figure 8B; see also Kablanow and Surdam, 1984). In the Huasna basin (Figure 8A), the Monterey Formation is overlain mainly by siltstone and sandstone of the Santa Margarita Formation.

Overlying the marine Pliocene sequence in most areas of the assessment province are upper Pliocene and Pleistocene non-marine gravel, sand, and silt deposits of the Paso Robles Formation (Figure 8).

Basic references for detailed stratigraphy in the assessment province are Canfield (1939), Woodring and Bramlette (1950), Dibblee (1950, 1966), Hall and Corbato (1967), Hall (1973a, 1973b, 1974, 1976, 1978, 1981a), Hall and Prior (1975), and Hall and others (1979).

SOURCE ROCKS

The Monterey Formation is generally thought to be the only significant source rock in the Santa Maria Basin assessment area, though other potential source rocks such as the Rincon Shale are locally present in the area.

Source-rock studies available at the time of the assessment that included samples from within the assessment province were few, mainly Surdam and Stanley (1981) for the Pismo

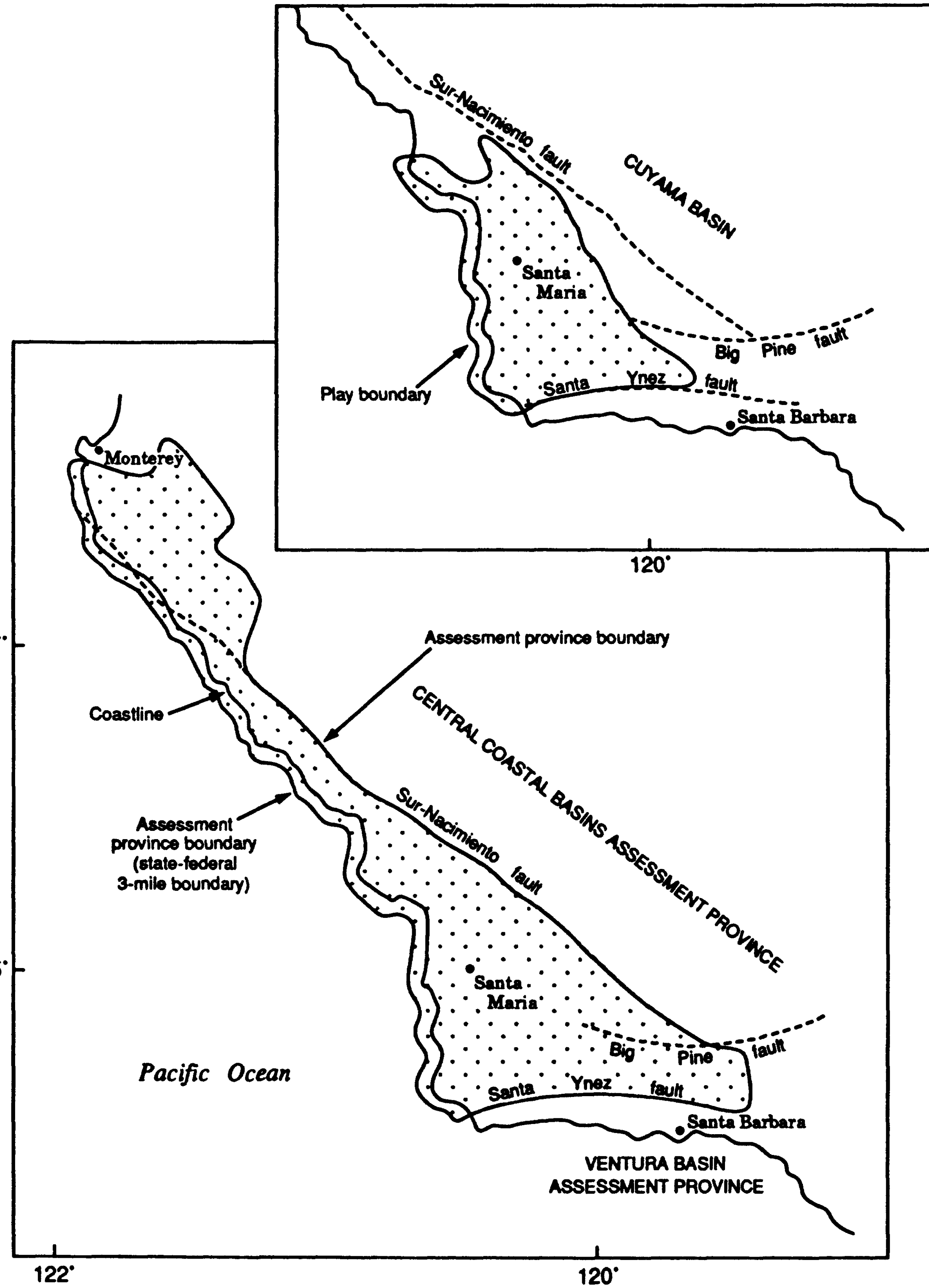


Figure 1A. Location of the Santa Maria basin assessment province and Neogene play boundary.

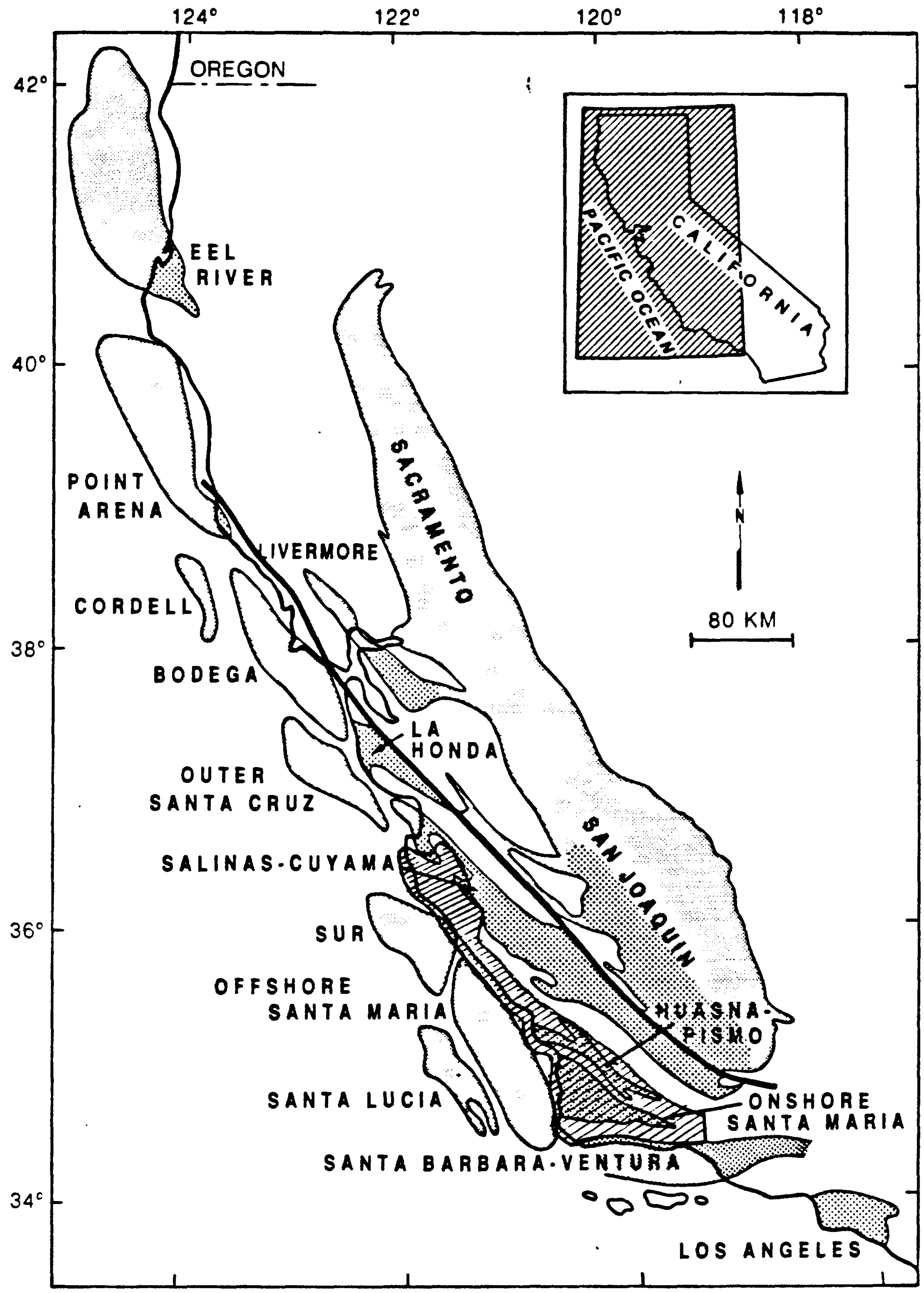


Figure 1B. Location of the Neogene basins of California (from Blake and others, 1978, and McCulloch, 1987, 1989). The lined area shows the assessment province.

Figure 1C. Oil and gas fields in the assessment province and adjacent areas to the south (from California Division of Oil and Gas, 1974).

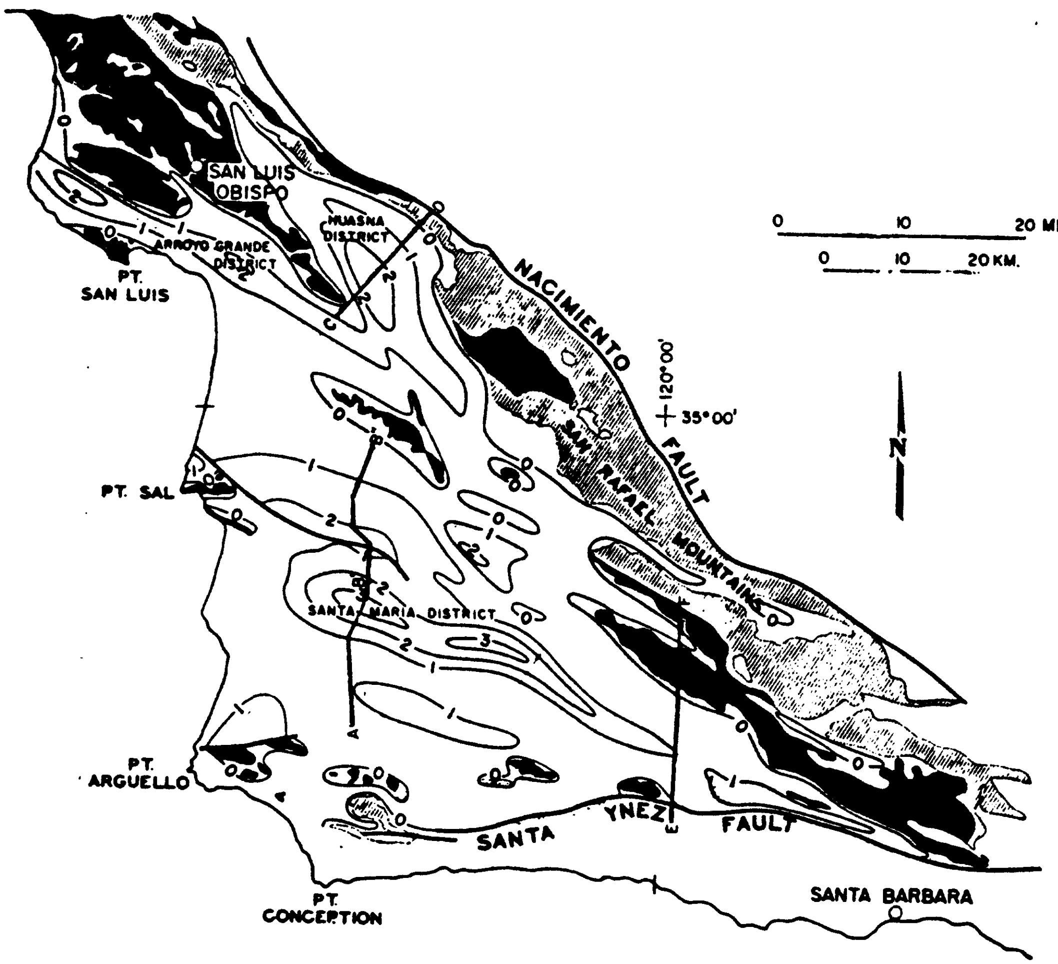


Figure 2. Generalized contour map of base of Tertiary, Santa Maria basin assessment province, California. Datum is sea level, contour interval is 1 mile. Black areas are Jurassic-Lower Cretaceous outcrops, hachured areas are Upper Cretaceous outcrops. Cross-sections A-B", C-D, and E-F (shown in Figure 5) are located. Reprinted from Crawford (1971) by permission.

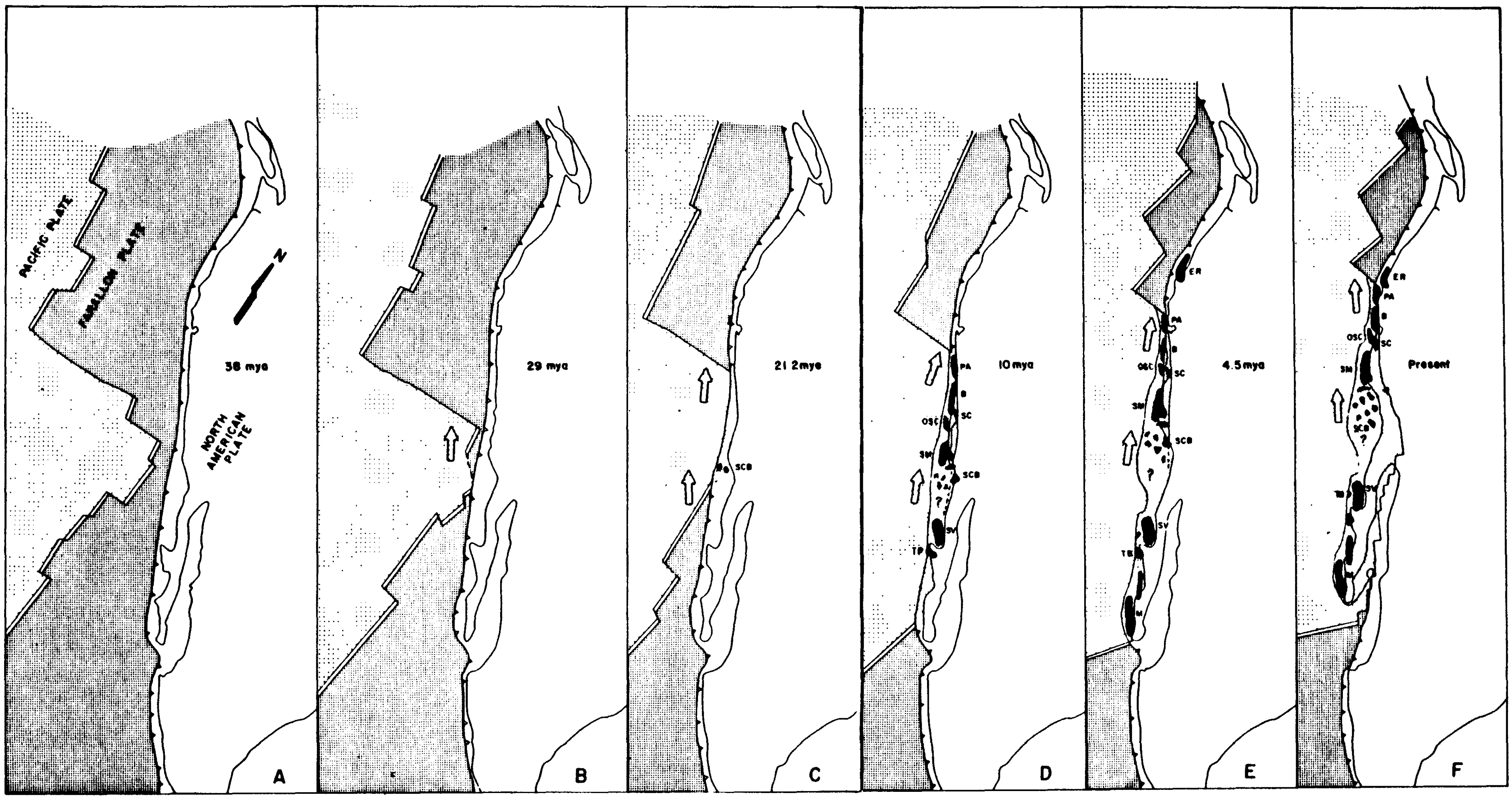
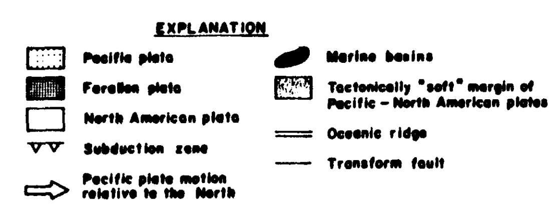
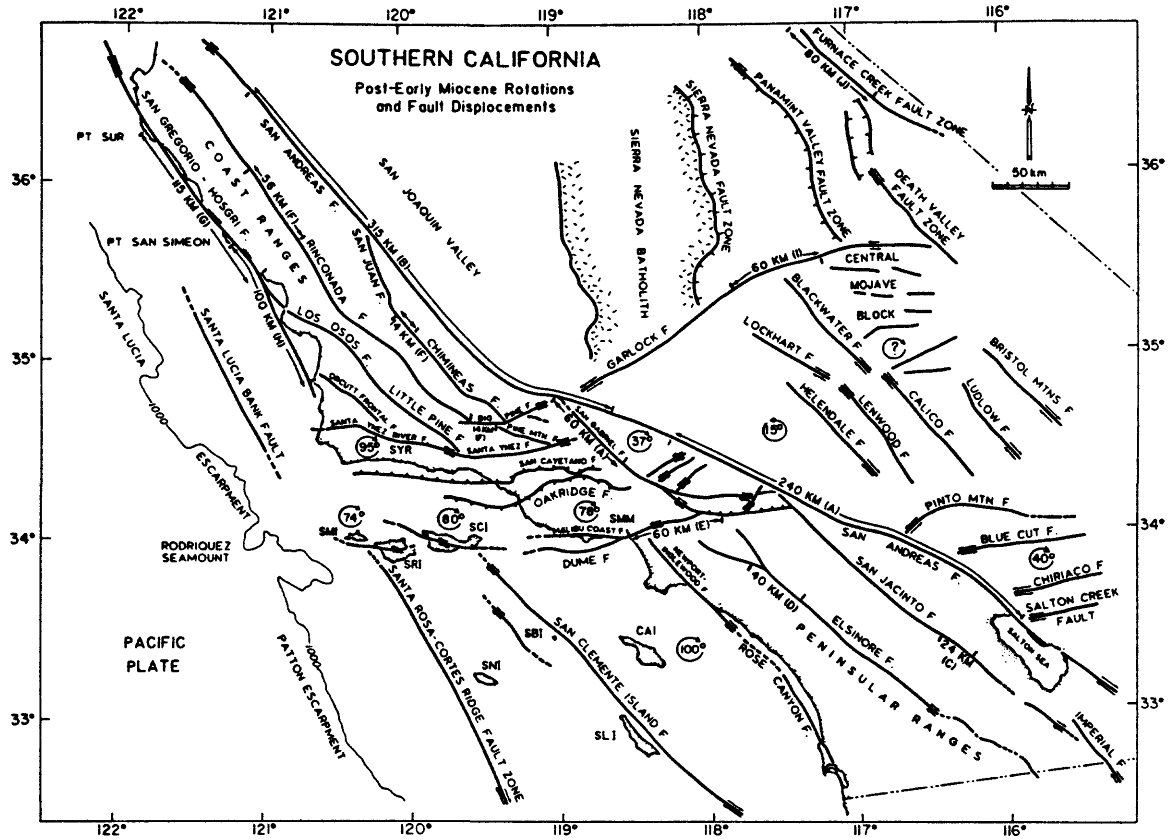


Figure 3. Schematic model of interaction of Pacific Farallon and North American plates for six Tertiary time intervals, showing time of initial development, location, and general shape of Neogene basins that formed (from Blake and others, 1978; based on Atwater and Molnar, 1973). ER, Eel River basin; PA, Point Arena basin; B, Bodega basin; SC, Santa Cruz basin; OSC, Outer Santa Cruz basin; SM, Santa Maria basin; SCB, Southern California basin; SV, Sebasian Vizcaino basin; TB, Tortugas basin; and M, Magdalena borderland.





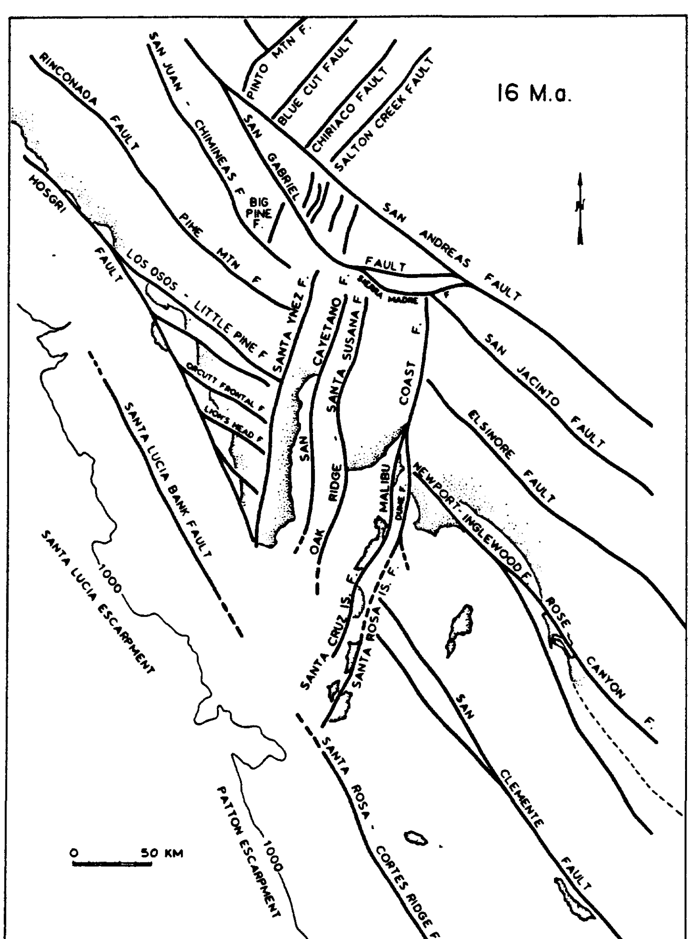


Figure 4. Present-day geography (above) and palinspastic reconstruction at 16 Ma (below) showing presentday faults and shorelines of southern California. Circular arrows indicate the sense and amount of tectonic rotation suggested by paleomagnetic data, with most rotation in the interval 10-16 Ma. Straight arrows indicate the amount of displacement between piercing points along major strike-slip faults. Reprinted from Hornafius and others (1986) by permission.

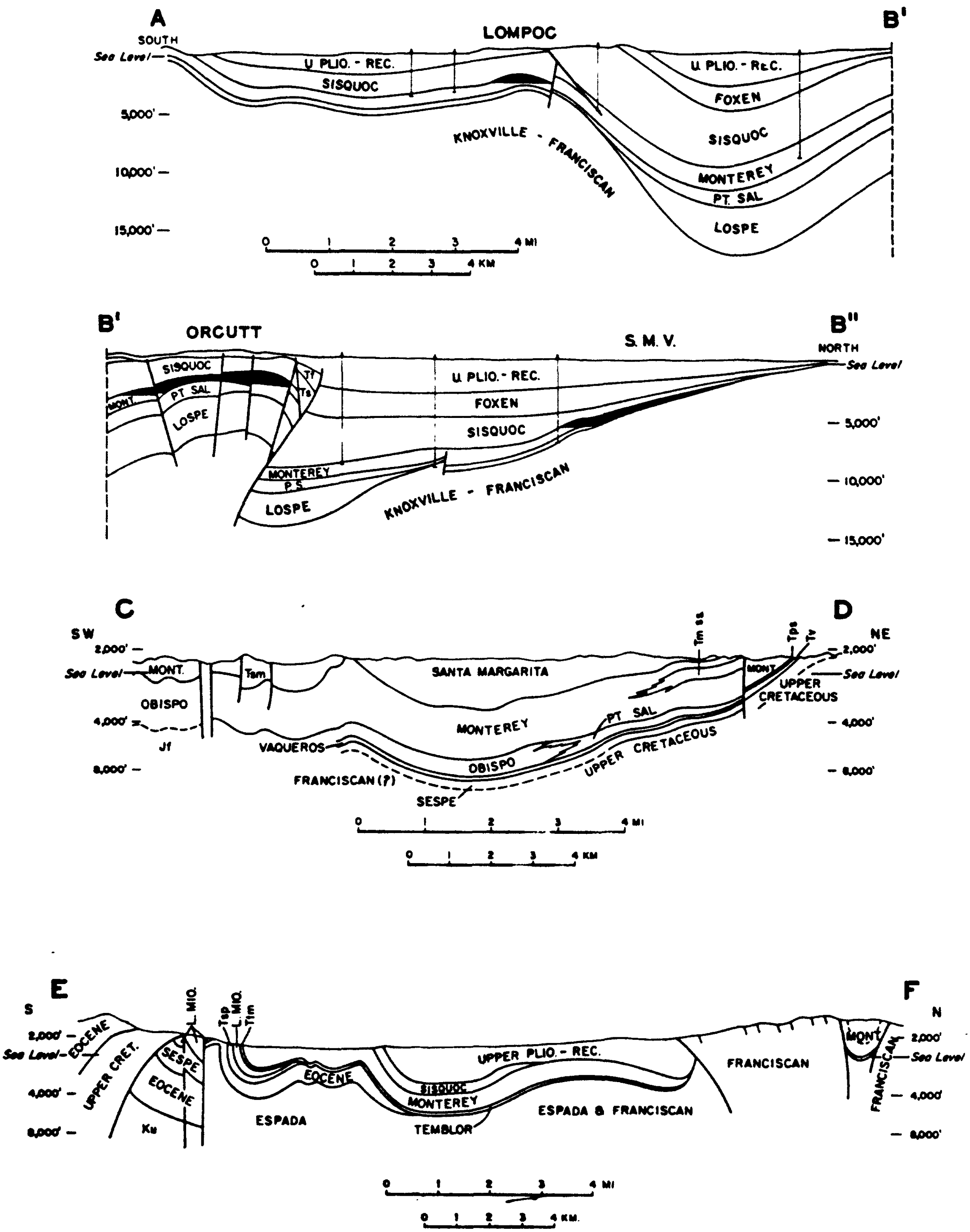


Figure 5. Cross sections in the Santa Maria Basin assessment province. A-B'-B" through Santa Maria district (from Crawford, 1971; based on Krammes, Curran, and others, 1959). C-D through Huasna district (from Crawford, 1971; based on Hall and Corbato). E-F across southeastern Santa Maria district (from Crawford, 1971; from Dibblee, 1966). Location of cross sections is shown in Figure 2. Reprinted from Crawford (1971) by permission.

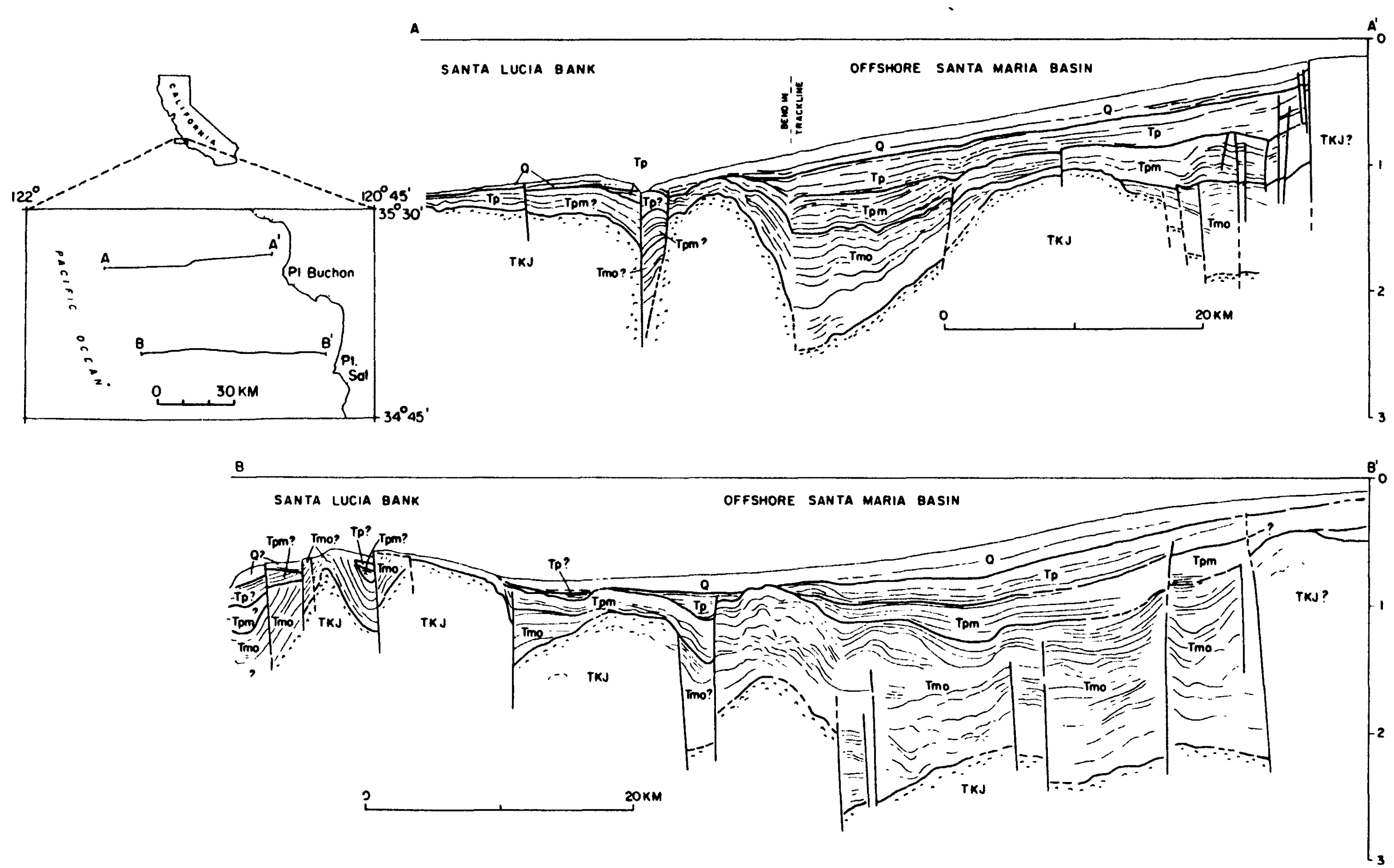
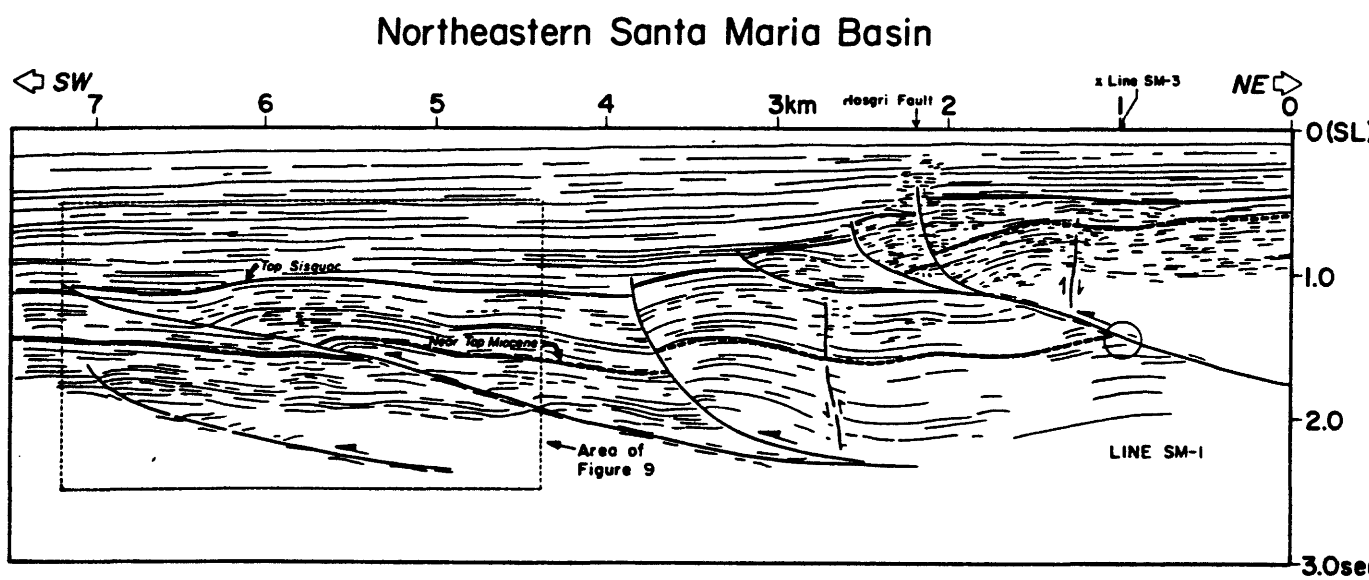


Figure 6A. An example of wrench tectonic interpretation of offshore Santa Maria basin (from Howell and others, 1980).



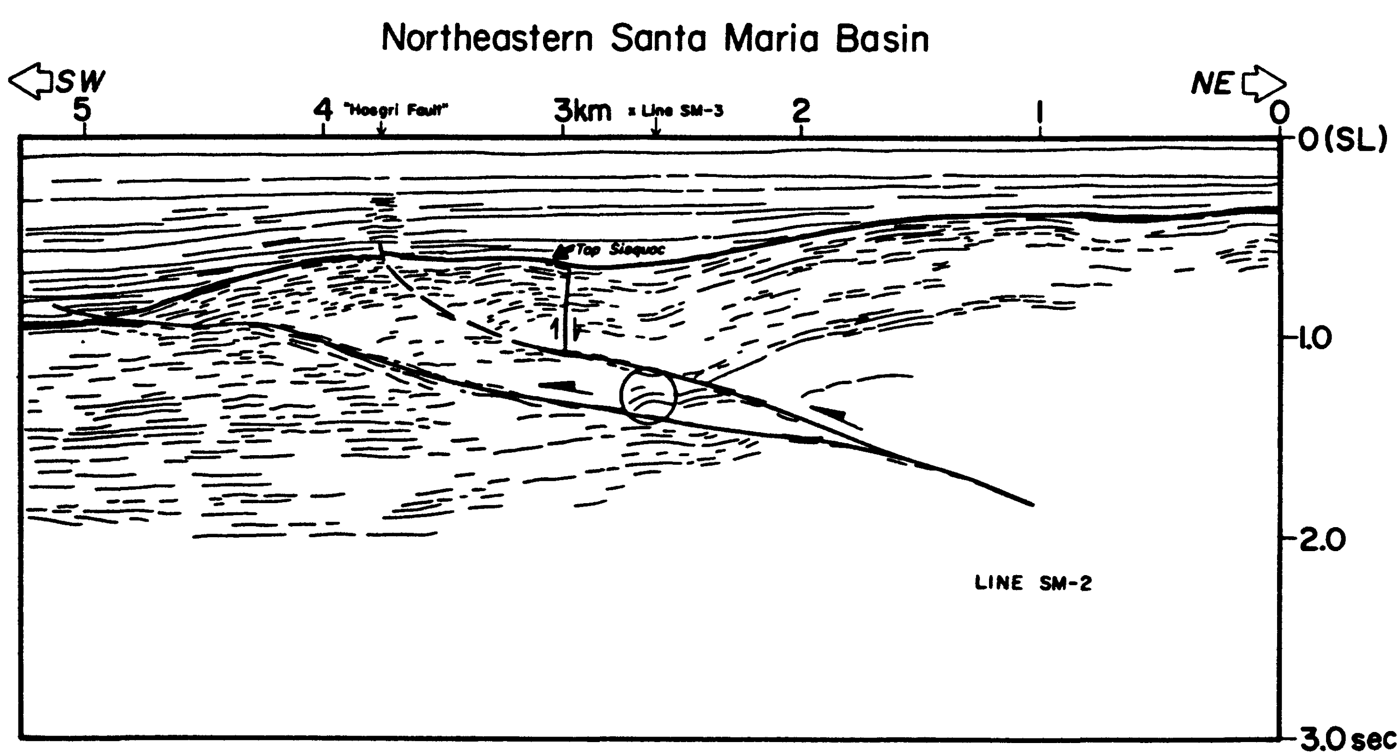


Figure 6B. An example of compressional tectonic interpretation of offshore Santa Maria basin off Point Sal (reprinted from Crouch and others, 1984, by permission).

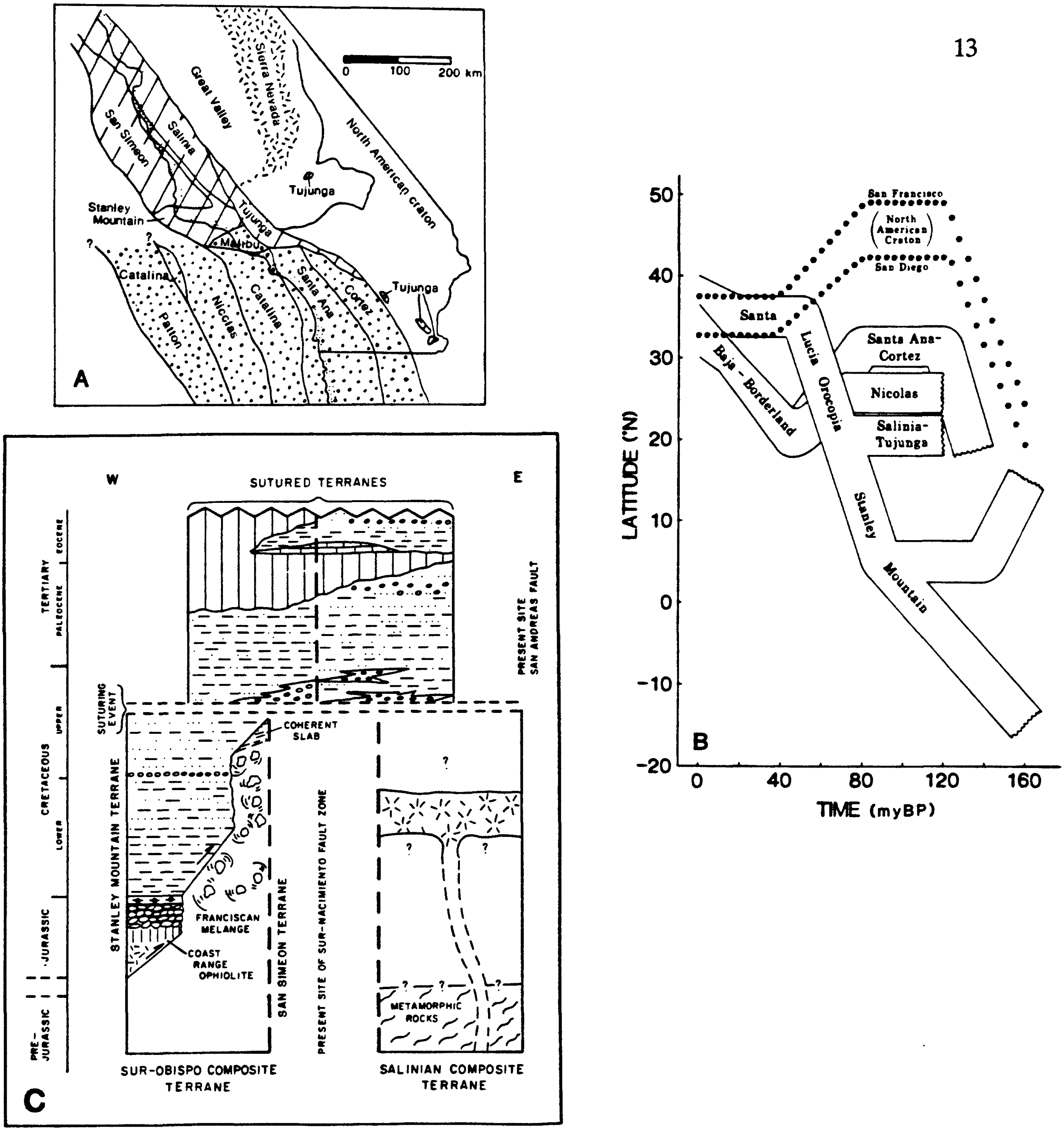


Figure 7. Pre-Eocene geologic history of the Santa Maria and Santa Barbara-Ventura basins. (A) Terranes of Southern California and northern Baja California showing the Santa Lucia-Orocopia allochthon (diagonal lines) and the Baja Borderland allochthon (stippled pattern). From Howell and others (1987). (B) Proposed latitude trajectories of the allochthons (and their constituent terranes) shown in A. From Howell and others (1987). (C) Generalized pre-Eocene stratigraphic column for the Salinian composite terrane, and the Sur-Obispo composite terrane (including the San Simeon terrane and the Stanley Mountain terrane). Modified slightly from Vedder and others (1983).

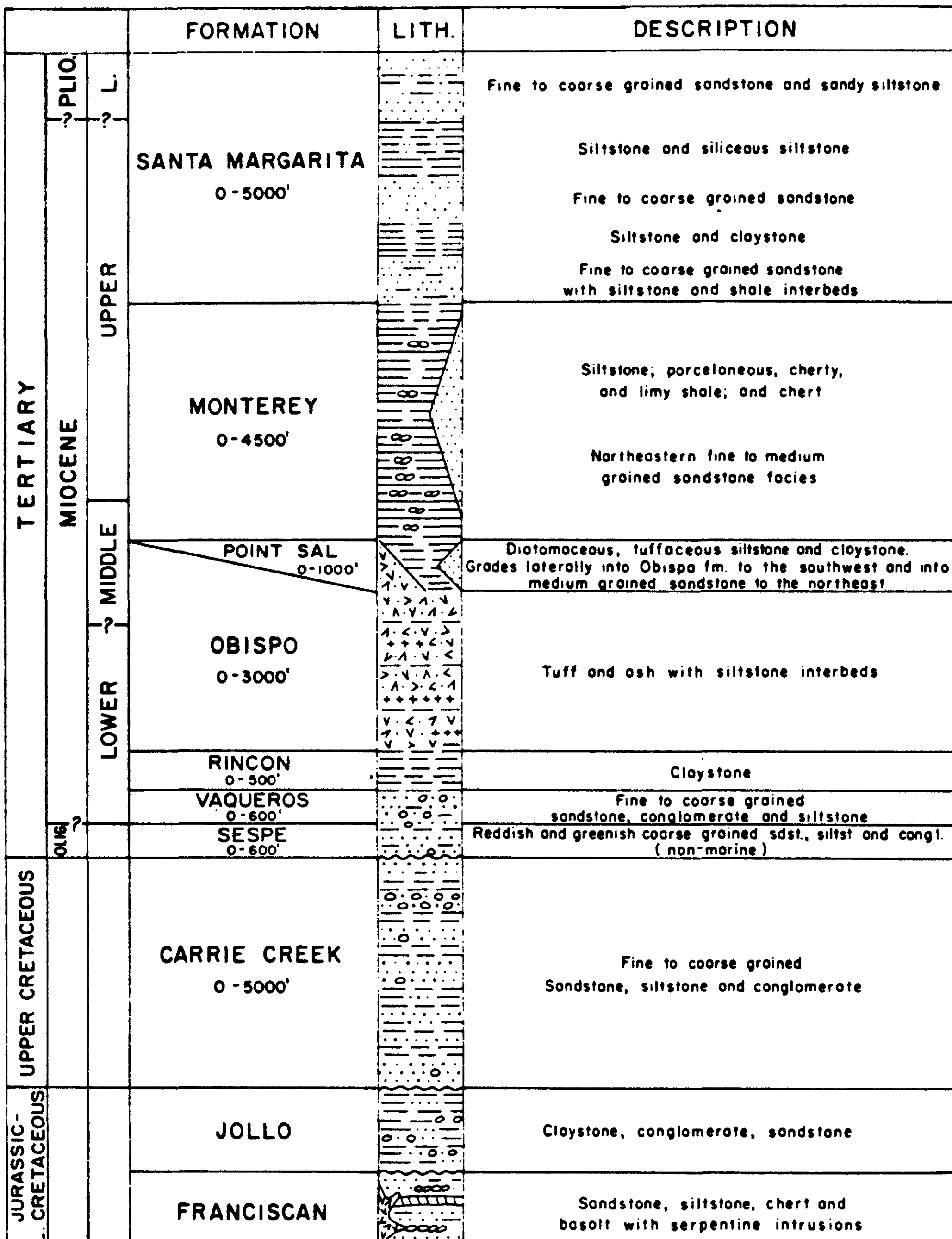


Figure 8A. Generalized stratigraphic section of Huasna district (reprinted from Crawford, 1971, by permission).

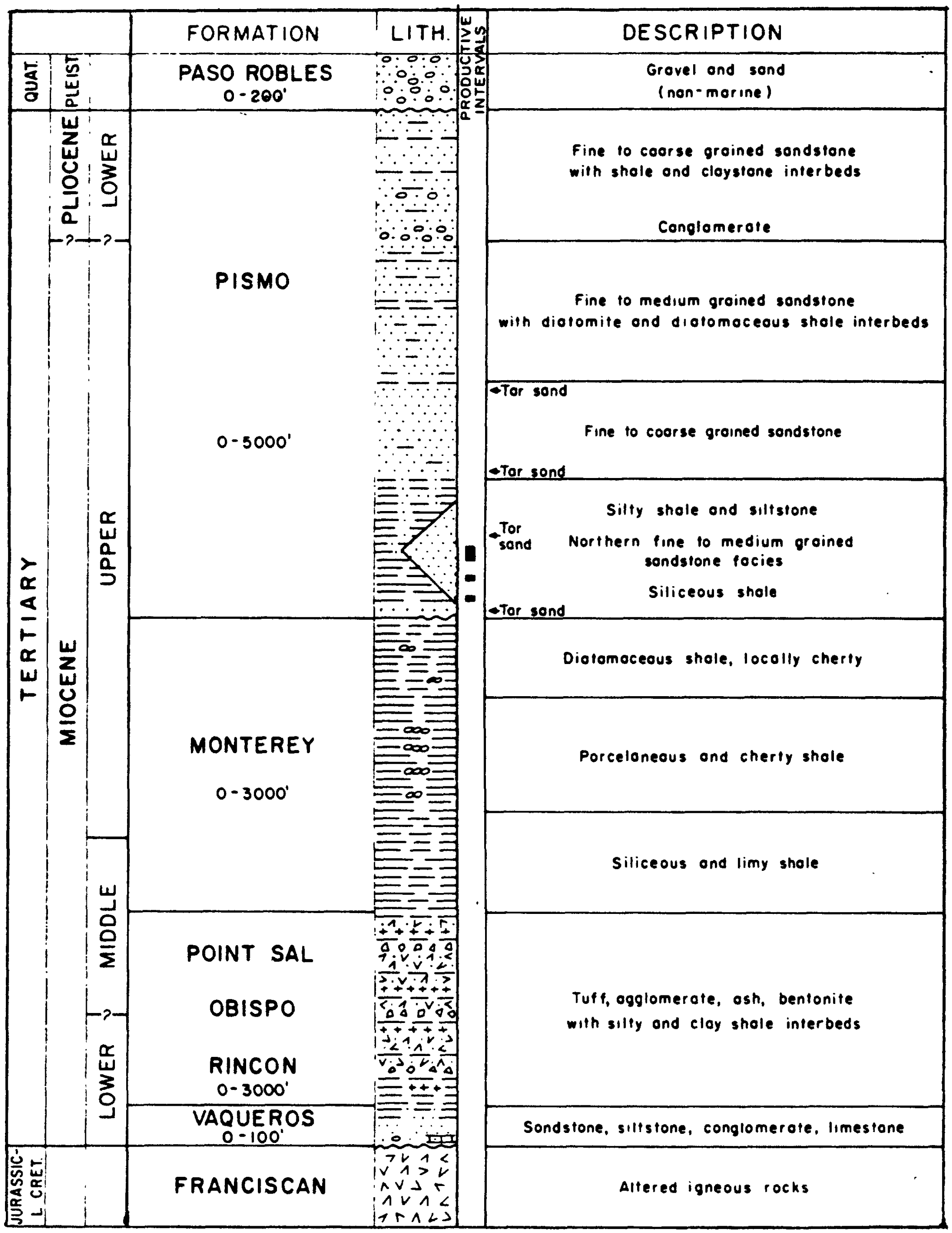


Figure 8B. Generalized stratigraphic section of Arroyo Grande district (reprinted from Crawford, 1971, by permission).

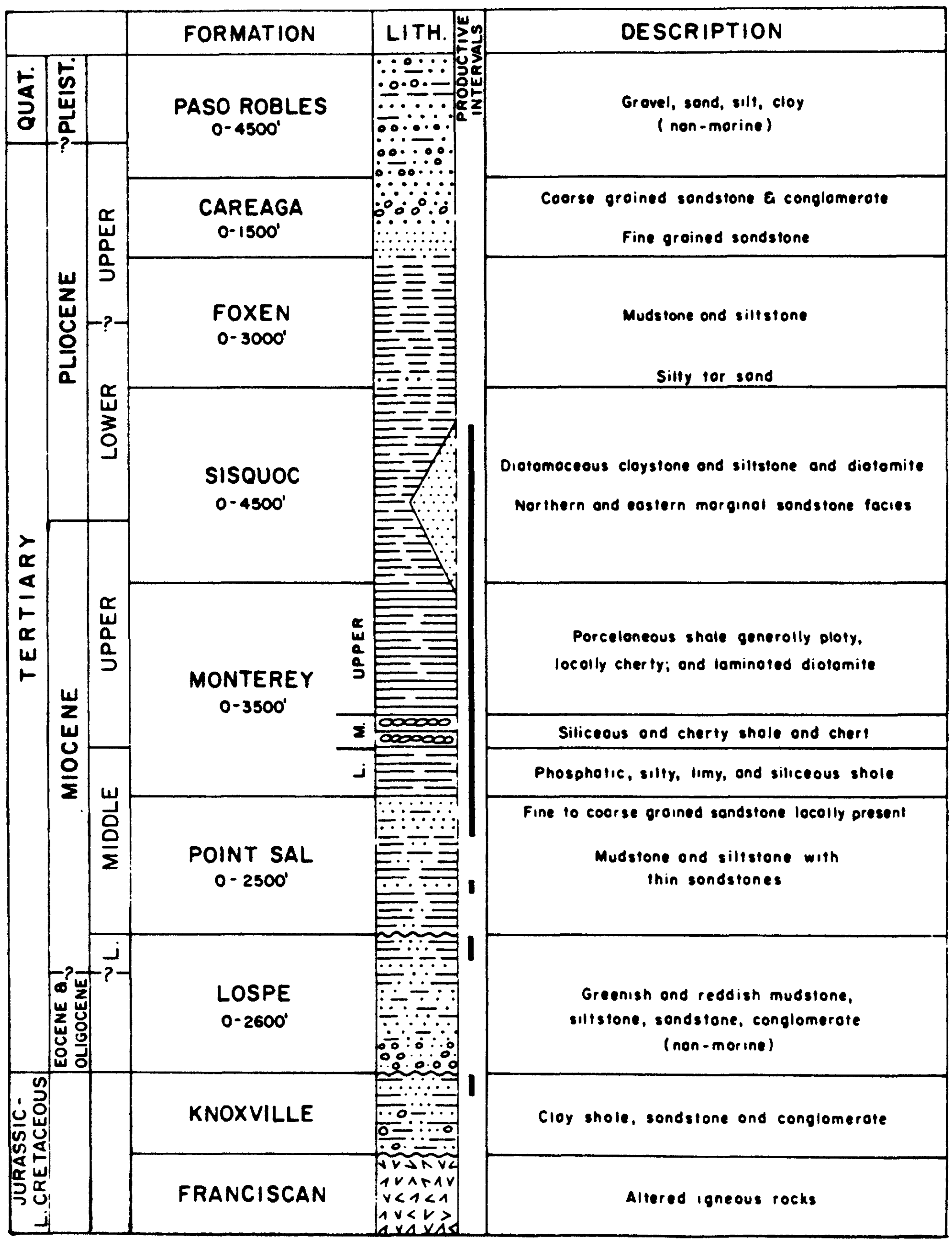


Figure 8C. Generalized stratigraphic section of central Santa Maria district (reprinted from Crawford, 1971, by permission).

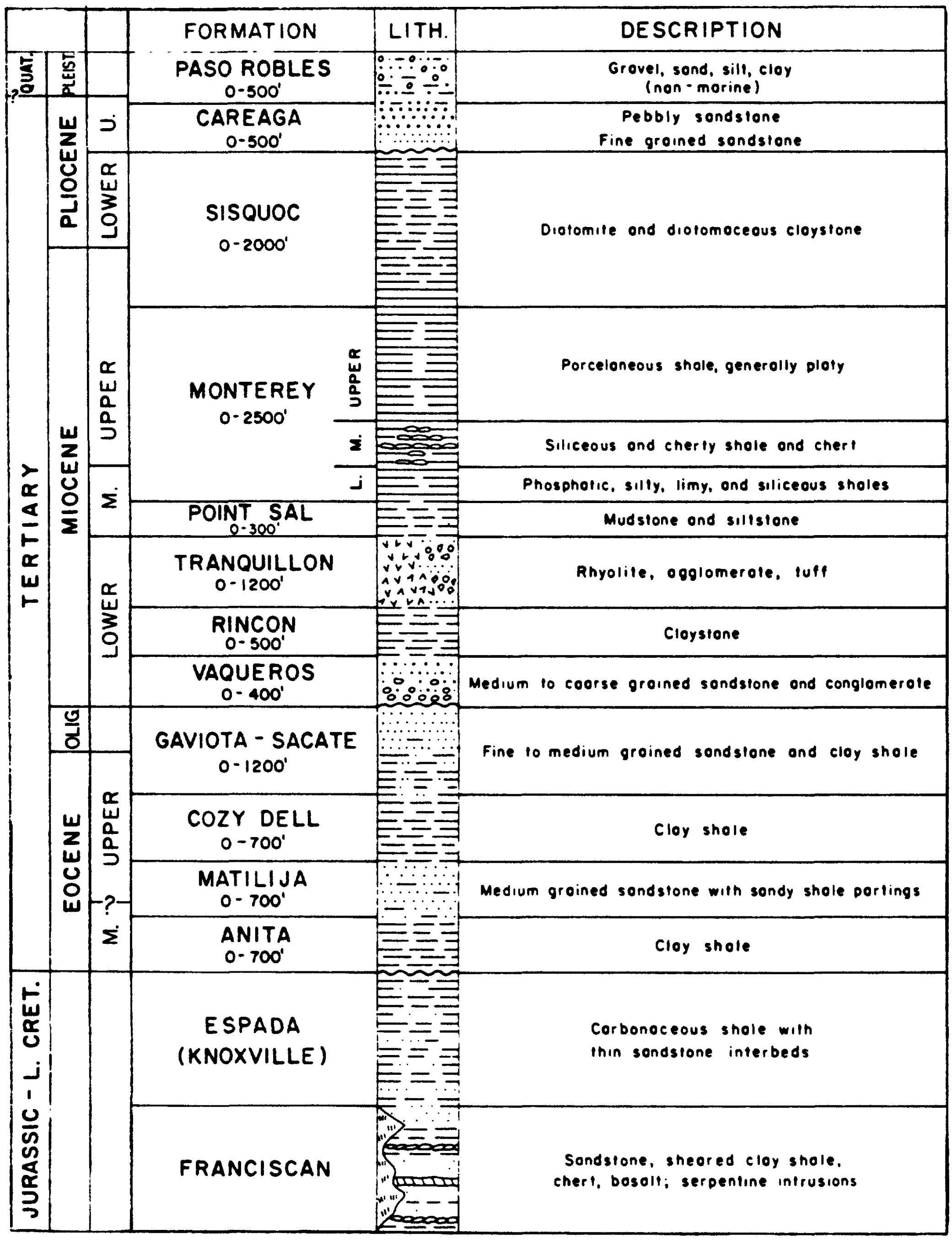


Figure 8D. Generalized stratigraphic section of southwestern Santa Maria district (reprinted from Crawford, 1971, by permission).

			FORMATION	LITH.	DESCRIPTION
QUAT.	PLEIST.		PASO ROBLES 0-3000'		Gravel, sand, silt, clay (non-marine)
TERTIARY	PLIO.	U.	CAREAGA 0-300'		Medium grained sandstone Fine to medium grained sandstone
TERTIARY	PLIO.	L.	SISQUOC 0-1000'		Diatomite and diatomaceous siltstone Eastern sandstone (Tequepis) facies
TERTIARY	MIOCENE	UPPER	MONTEREY 0-2500' — UPPER		Siliceous and silty shale, generally platy
TERTIARY	MIOCENE	UPPER	MONTEREY 0-2500' — M.		Porcelaneous shale, generally platy, locally cherty
TERTIARY	MIOCENE	M.	MONTEREY 0-2500' — L.		Organic, phosphatic, clay shale
TERTIARY	MIOCENE	M.	TEMBLOR (PT. SAL) 0-600'		Fine to medium grained sandstone, locally tuffaceous
TERTIARY	MIOCENE	LOWER	RINCON 0-1000'		Clay shale and silty shale
TERTIARY	MIOCENE	LOWER	VAQUEROS 0-600'		Fine to medium grained sandstone and sandy siltstone
TERTIARY	OLIG.		SESPE 0-1500'		Fine to coarse sandstone, conglomerate, and reddish and greenish silty shale (non-marine)
TERTIARY	EOCENE	UPPER	COLDWATER 0-600'		Fine to coarse grained sandstone with siltstone interbeds
TERTIARY	EOCENE	UPPER	COZY DELL 0-1000'		Clay shale and silty shale
TERTIARY	EOCENE	?	MATILIJA 0-800'		Fine to coarse grained sandstone with minor siltstone interbeds
TERTIARY	EOCENE	MIDDLE	JUNCAL 0-1200'		Clay shale and silty shale with thin sandstone interbeds
TERTIARY	EOCENE	MIDDLE	SIERRA BLANCA 0-20'		Sandy limestone
JURASSIC - L. CRET.			ESPADA (KNOXVILLE)		Carbonaceous shale with thin sandstone interbeds
JURASSIC - L. CRET.			FRANCISCAN		Sandstone, sheared clay shale, chert

Figure 8E. Generalized stratigraphic section of southeastern Santa Maria district (reprinted from Crawford, 1971, by permission).

area, Kablanow and Surdam (1984) for the Huasna area, and Curiale and others (1985), Orr (1986), and a study later released as Isaacs and Tomson (1990) for the onshore Santa Maria area. Some data was also available for the Point Conception DST well in the offshore Santa Maria basin (Claypool and others, 1979; King and Claypool, 1983; Petersen and Hickey, 1984, 1987).

Reported values for total organic carbon (TOC) are 1-5% (av 2-3%) for the Monterey Formation in the Pismo basin (Surdam and Stanley, 1981). In the Santa Maria basin, reported values for TOC are 0.7-8% (av 1%) for the Sisquoc Formation, 1-18% (av 6%) for the Monterey Formation, and 1-4% (av 2%) for the Point Sal Formation (Isaacs and others, 1989, 1990). In general, Monterey strata are classed as type II kerogen thought to have derived mainly from marine algal sources with varying contributions from terrigenous sources (Surdam and Stanley, 1981; Kablanow and Surdam, 1984; Isaacs and Tomson, 1990). Because of its sulfur richness, the kerogen type has come to be generally known subsequent to the assessment as type II-S (e.g., Heasler and Surdam, 1989).

BURIAL HISTORY, THERMAL MATURITY, AND TIMING OF MIGRATION

The main burial histories available at the time of the assessment were Pisciotto (1981) for the onshore Santa Maria basin, Heasler and Surdam (1983, 1985) for the Pismo basin, and Kablanow and Surdam (1984) for the Huasna basin. All these histories were limited by lack of measured equilibrium thermal gradients (which have been published for only one well in each of the Santa Maria Valley, Orcutt, and Lompoc fields by French, 1940) and lack of empirical evidence about paleogradients.

At the time of the assessment, models of maturation and thermal history in the Santa Maria Basin assessment province had been complicated by two newly discovered problems: (1) misleading and difficult-to-interpret maturity parameters; and (2) misleading and difficult-to-construct thermal models.

Maturity parameters are misleading and difficult-to-interpret probably because of both compositional characteristics of the kerogen (sparse vitrinite, high sulfur) and oil generation after comparatively short time-temperature histories (Milner and others, 1977; McCulloh, 1979; Walker and others, 1983; Petersen and Hickey, 1984, 1987; Heasler and Surdam, 1983, 1985, 1989; Orr, 1986). For most purposes, maturity parameters in the Monterey Formation are considered unreliable or of little value (for a summary, see Isaacs and Petersen, 1987).

Thermal models are misleading and difficult-to-construct because of both unusual porosity and thermal conductivity characteristics of diatomaceous rocks and uncertainties in the thermal history (for a summary, see Isaacs and Petersen, 1987). Combined with unreliable maturity parameters, for most purposes thermal models are highly speculative and of questionable value for predicting oil generation. However, ongoing research on these topics subsequent to the 1987 assessment may be providing useful approaches to predictive understanding (e.g., Heasler and Surdam, 1989; King and Lillis, 1990).

Potential deep hydrocarbon generation areas in the onshore Santa Maria basin lie in the major synclinal areas between the Santa Maria Valley and Orcutt fields and between the Orcutt and Lompoc fields. In both these synclinal areas, the Monterey Formation shows greater diagenetic grade and thermal maturity than in adjacent structurally high areas (Pisciotto, 1981; Isaacs and Tomson, 1990).

On the basis of thickness differences in the Sisquoc Formation and younger strata across the major anticlinal structures (see for example Figure 5, section A-B"), growth of these structures has long been regarded as having begun in the late Miocene about coincident with the boundary between the Sisquoc and Monterey Formations (Woodring and Bramlette, 1950). Growth of these trapping structures has presumed to have preceded the migration of most generated hydrocarbons (Crawford, 1971). Subsequent to the assessment, a new structural interpretation suggested that the formation thickness differences might be due to fault-repetitions in a later compressional tectonic regime (Namson and Davis, 1990). If this interpretation is correct, the major anticlinal trapping structures may have developed at a later time than previously thought, and earlier formed trap types (such as sandstone pinchouts) might have accumulated earlier-migrating oil (Lillis and King, 1991).

HYDROCARBON OCCURRENCE

Geographic Distribution

Of total discovered oil and gas resources in the assessment province, the vast majority (>99%) have been located in the onshore Santa Maria basin, somewhat less than 1% derive from the Arroyo Grande field in the Pismo basin, and very minor amounts (≈ 0.03 MMbbl) from the Huasna and Lopez Canyon fields in the Huasna basin (Figure 1B, Table 3). All areas in the assessment province within state waters (within 3 miles of the coastline) remain undrilled.

Stratigraphic and structural habitat of petroleum

Most oil in the onshore Santa Maria geologic basin occurs in various fine-grained rock types of the Miocene Monterey Formation, and in shales and sandstones of the overlying latest Miocene and early Pliocene Sisquoc Formation and underlying early Miocene Point Sal Formation (Tables 1 and 3). Minor oil is also reported in the Pliocene Foxen Formation, and in fractured sandstones of the Lospe Formation and upper Cretaceous "Knoxville" or Espada Formation. In the Pismo geologic basin (Arroyo Grande field), oil is produced from permeable sandstones of the Pismo or Santa Margarita Formation.

An unusual characteristic of oil reservoirs in the assessment area is the predominance of fractured reservoirs. According to Crawford's (1971) estimates, 75% of cumulative production at the time derived from fractured Monterey reservoirs, 2% from other fractured rock, and only 23% from permeable sandstone reservoirs. Fractured Monterey reservoirs are also significant in adjacent offshore areas such as the Point Arguello field in the offshore Santa Maria basin (Crain and others, 1985, 1987) and the Hondo field in the Santa Barbara Channel (operator report in U.S. Geological Survey, 1974). A characteristic of fractured reservoirs is difficulty in identifying the presence of reservoirs due to their lack of oil shows and their disregard of conventional rules-of-thumb for well-log interpretation (for a summary, see Isaacs and Petersen, 1987).

Within the assessment area, petroleum traps are of two major types: structural (anticlinal) and stratigraphic (overlap truncation or sandstone pinchout). Schematic examples of typical traps are shown in Figure 9. According to Crawford's (1971) estimates, 58% of cumulative production at the time had derived from major fields which he characterized as anticlinal traps (all of which produce mainly from fractured Monterey reservoirs), and 38% of cumulative production from fields which he characterized as stratigraphic traps (which produce from truncated fractured Monterey shale overlapped by Sisquoc strata or from lenticular Sisquoc sandstones); he estimated that 4% of cumulative production had derived from overlapped pre-Monterey hard sandstone units and from tar-sealed sandstones. Subsequent to the assessment, however, re-evaluation showed that several fields such as the Zaca field characterized by Crawford (1971) as stratigraphic traps are generally classed (e.g., California Division of Oil and Gas, 1974) as structural traps; thus cumulative production from stratigraphic traps is more likely to be less than 38%, perhaps in the range 20-25%.

Basis for play definition

The major distinction among fields considered for play definition was reservoir type (fractured "shale" vs. permeable sandstone). As classed by reservoir horizon, however, over 90% of production (through 1983) had derived from fields with both fractured reservoirs and conventional sandstone reservoirs (California Division of Oil and Gas, 1974), and many individual wells produce commingled oils. Further, production has not historically been tabulated by field area and reservoir pool throughout the assessment province. Because the methodology of the assessment was based on field discovery history and field size distribution, a distinction between reservoir types was thus not practical.

Another possible distinction among fields for play definition might be trap type (structural vs. stratigraphic). However, as classed by trap type, about 35% of production has derived solely from structural traps but nearly all the remaining production has derived from fields with a combination of trap types.

Because of the small number of fields in the assessment province (14 major fields as classed by the Nehring data), the single hydrocarbon source, the regional similarity of trap types (or combination of types), and the impracticality of cleanly dividing fields into categories with production data, all fields in the assessment area were grouped together in a single play termed the Neogene play.

NEOGENE PLAY

Play Definition

The Neogene play is characterized by oil accumulations reservoired in Neogene or subjacent strata by structural, stratigraphic, and combination structural-stratigraphic traps. The play includes the Tertiary onshore Santa Maria, Huasna, and Pismo basins together with adjacent state waters, an area approximately 60 miles long and 20-50 miles wide (Figure 1A).

Reservoirs

The major reservoir is fractured fine-grained Monterey strata estimated by Crawford (1971) as accounting for about 75% of cumulative production. According to Regan and Hughes (1949), the most important fractured reservoir lithologies are chert zones followed by calcareous shale zones, with platy siliceous and porcelaneous shale zones of minor economic importance. Dolostone may also be an important reservoir lithology locally (Redwine, 1981; Roehl, 1981). In these reservoirs, porosity values are of little significance because production is mainly the result of fracture-induced permeability adding only 1-2% porosity to matrix porosity values (Regan and Hughes, 1949; Crain and others, 1985; for summary and discussion, see Isaacs and Petersen, 1987). Other minor fractured reservoir horizons (estimated at 2% of production) include hard sandstones of the Knoxville, Lospe, and Point Sal Formations (Crawford, 1971).

The second major reservoir type is permeable sandstone of the Sisquoc, Point Sal, and (in the Arroyo Grande field) Pismo Formations (Crawford, 1971). Production from Sisquoc sandstones is mainly in the Cat Canyon, Santa Maria Valley, and Guadalupe fields, and from Point Sal sandstones in the main area of the Santa Maria Valley field, Orcutt field, and Casmalia field. Lagoe (1987) indicated that the Point Sal in the Orcutt field is a bathyal turbidite sequence likely derived from a northerly direction, whereas the Sisquoc sandstones are a shallow-water marginal facies (Woodring and others, 1943; Woodring and Bramlette, 1950).

Traps and seals

The simplest traps in the onshore Santa Maria basin are major faulted anticlinal traps, including the Orcutt (Figure 9A), Casmalia, and Lompoc oil fields. A few small fields are characterized solely by stratigraphic traps, such as the Central area of the Cat Canyon field (which produces from a Sisquoc sandstone pinch-out) and the West area of the Santa Maria Valley field. Most fields in the basin, however, are complex traps classed as combination structural-stratigraphic traps (NRG Associates, 1984). A good example is the West Cat Canyon field (Figure 9C) which originally produced (from 1908 to 1938 in both the original part of the field and a then-separate area termed "Doheny-Bell") from sandstone lenses in the Sisquoc Formation (Woodring and Bramlette, 1950). Later production in the field (since 1938) has been mainly from deeper Monterey reservoirs in a faulted anticline (Woodring and Bramlette, 1950; California Division of Oil and Gas, 1974).

Seals are equally complex. For overlap-truncation stratigraphic traps at the Monterey-Sisquoc formational boundary and lenticular sands within the Sisquoc and Pismo Formations, fine-grained Sisquoc or Pismo strata provide the seal. Within the Monterey Formation, abundant seals are available because matrix permeability (non-fracture permeability) is extremely low. Porosity and permeability barriers due to variations in fracturing are probably the principal seal. In the Guadalupe field, cemented conglomerate is the main seal (Woodring and Bramlette, 1950).

Oil Characteristics

Oil in the assessment province is generally heavy asphaltic oil with API gravities less than 20°. Although included in the assessment as conventional resources, most resources in the area are thus classed as unconventional by usual definition.

Much debate surrounds the reason for the generation of these heavy oils. Heavy oil may result from biodegradation, but work in the late 1970s and early 1980s suggested that the heavy oils in the Santa Maria area are instead mainly primary heavy oils representing "early" generation (Milner and others, 1977; Petersen and Hickey, 1983, 1984, 1987; Curiale, 1985; Orr, 1986). "Early" generation (i.e., generation at levels of thermal metamorphism conventionally thought to be pre-generative for oil) is attributed to low-activation kerogen (Petersen and Hickey, 1984, 1987). According to Petersen and Hickey (1984, 1987), Monterey-derived oils typically contain an unusually large proportion of non-hydrocarbon compounds (41% for Monterey oil average vs. 14% for world-wide oil average) and a comparatively small proportion of saturated hydrocarbons (27% for Monterey oil average vs. 58% for world-wide oil average). Organic-geochemical indications of immaturity are many, including a marked even-predominance in normal alkane profiles, also characteristic of the source kerogen (for a summary, see Petersen and Hickey, 1987; Isaacs and Petersen, 1987).

In addition to being heavy, oil in the assessment province tends to be rich in sulfur, with average values of about 5% (Orr, 1986). Sulfur in oils correlates inversely with API gravity, and high sulfur oil is generally heavy (Orr, 1986). Orr (1986) suggested that the cause of early generation was the relative ease of breaking C-S bonds in high-sulfur kerogen (type II-S) and hypothesized that the good-quality high-gravity oils in the Barham Ranch area were due to low-sulfur kerogen sources in this area.

Depth of Occurrence

The depth to the top of oil reservoir horizons is moderate, being on average less than 6000 ft in all fields (as listed in the Nehring data base) with an average depth of about 3000 ft. Reservoir thickness ranges from less than 50 ft to more than 3000 ft, with an average of about 900 ft. The shallowest average reservoir depths (<1000 ft) are in the Casmalia and

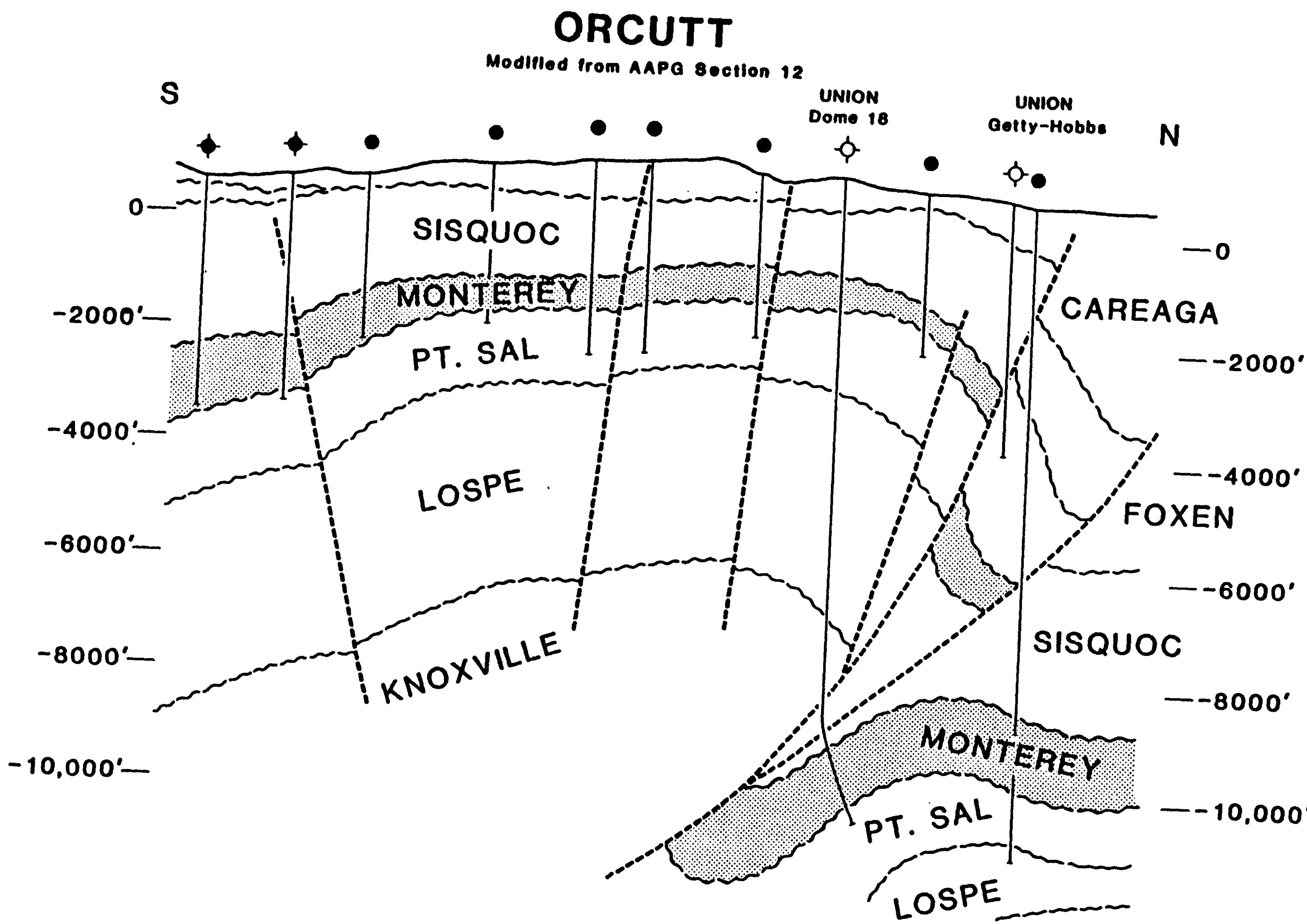


Figure 9A. Example of anticlinal trap, cross section of Orcutt field (from Katherman, 1983).

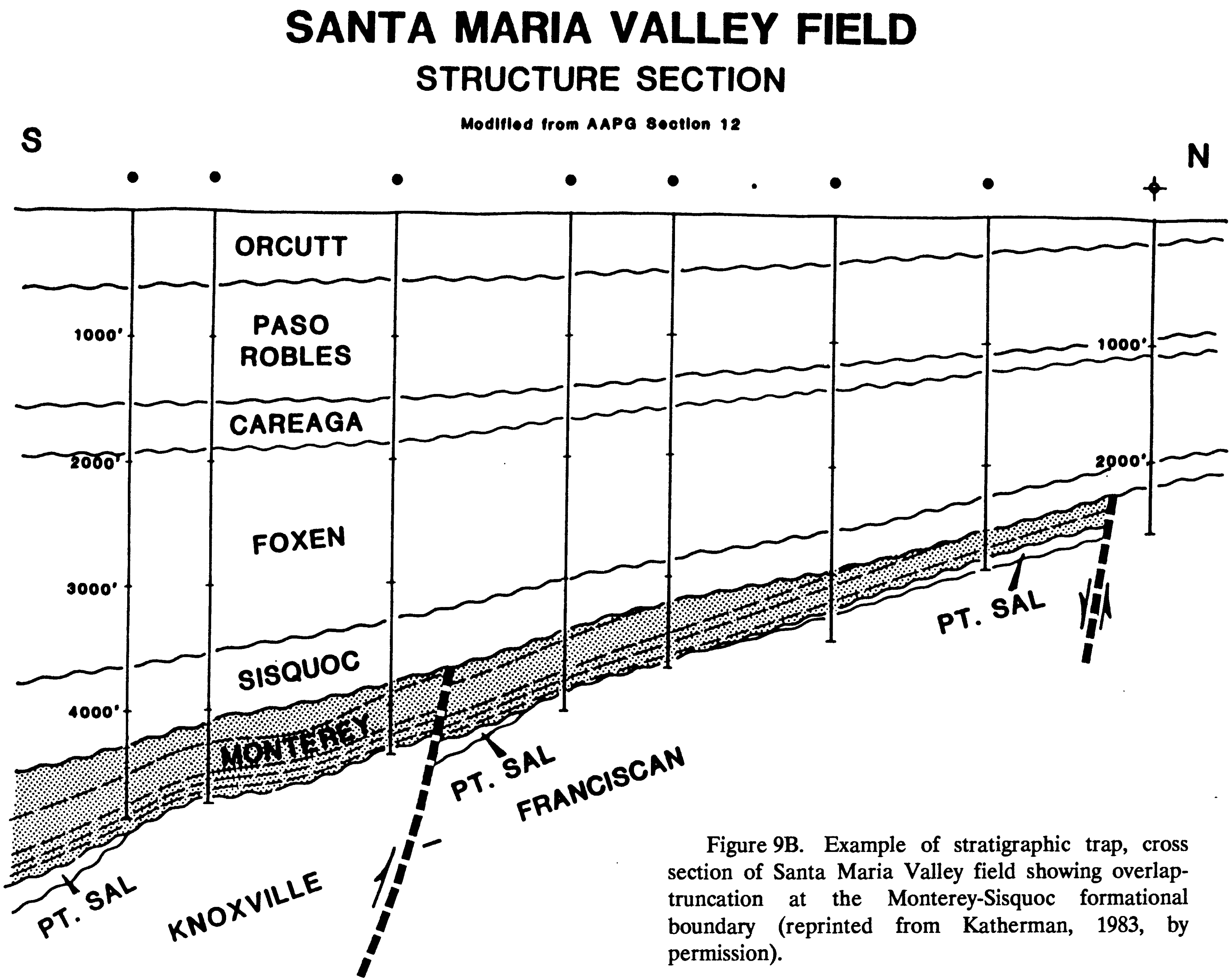


Figure 9B. Example of stratigraphic trap, cross section of Santa Maria Valley field showing overlap-truncation at the Monterey-Sisquoc formational boundary (reprinted from Katherman, 1983, by permission).

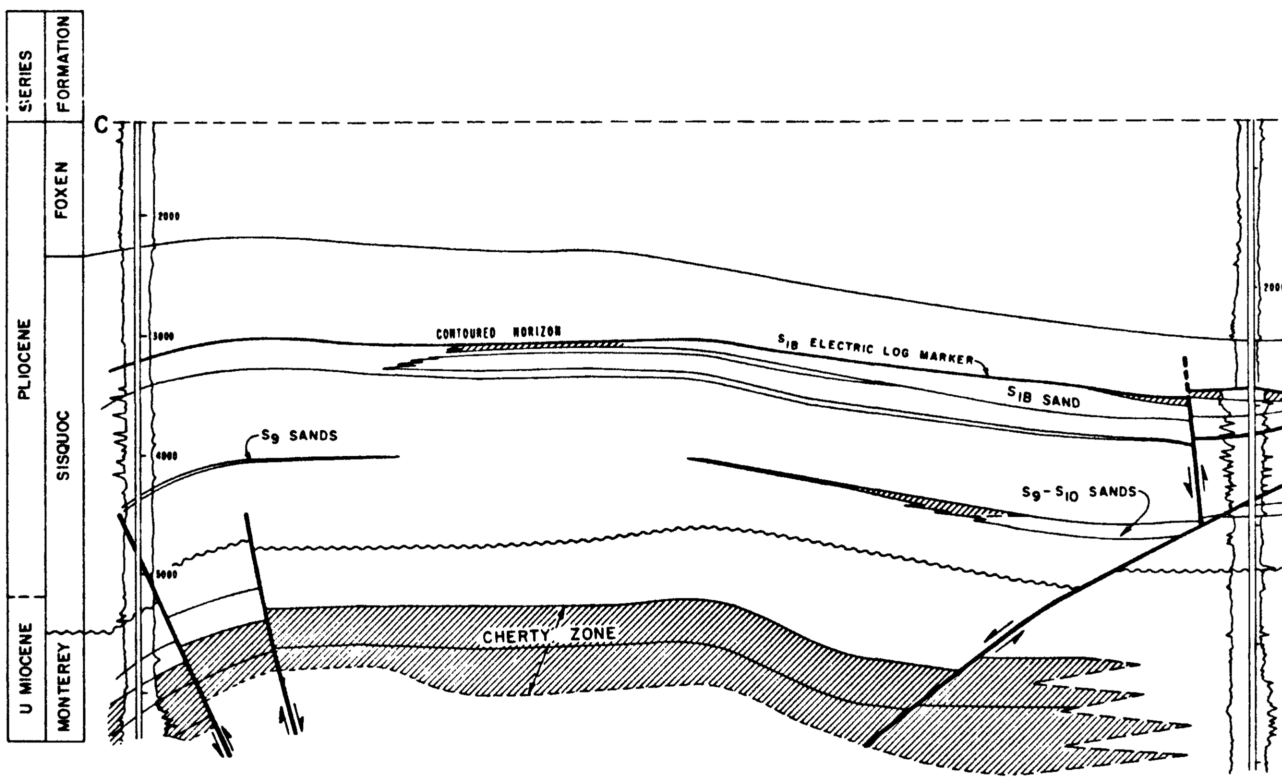


Figure 9C. Example of combination trap, cross section of the West area of the Cat Canyon field showing stratigraphic trap in Sisquoc sandstones, and later-discovered structural trap in underlying Monterey fractured reservoirs (from California Division of Oil and Gas, 1974).

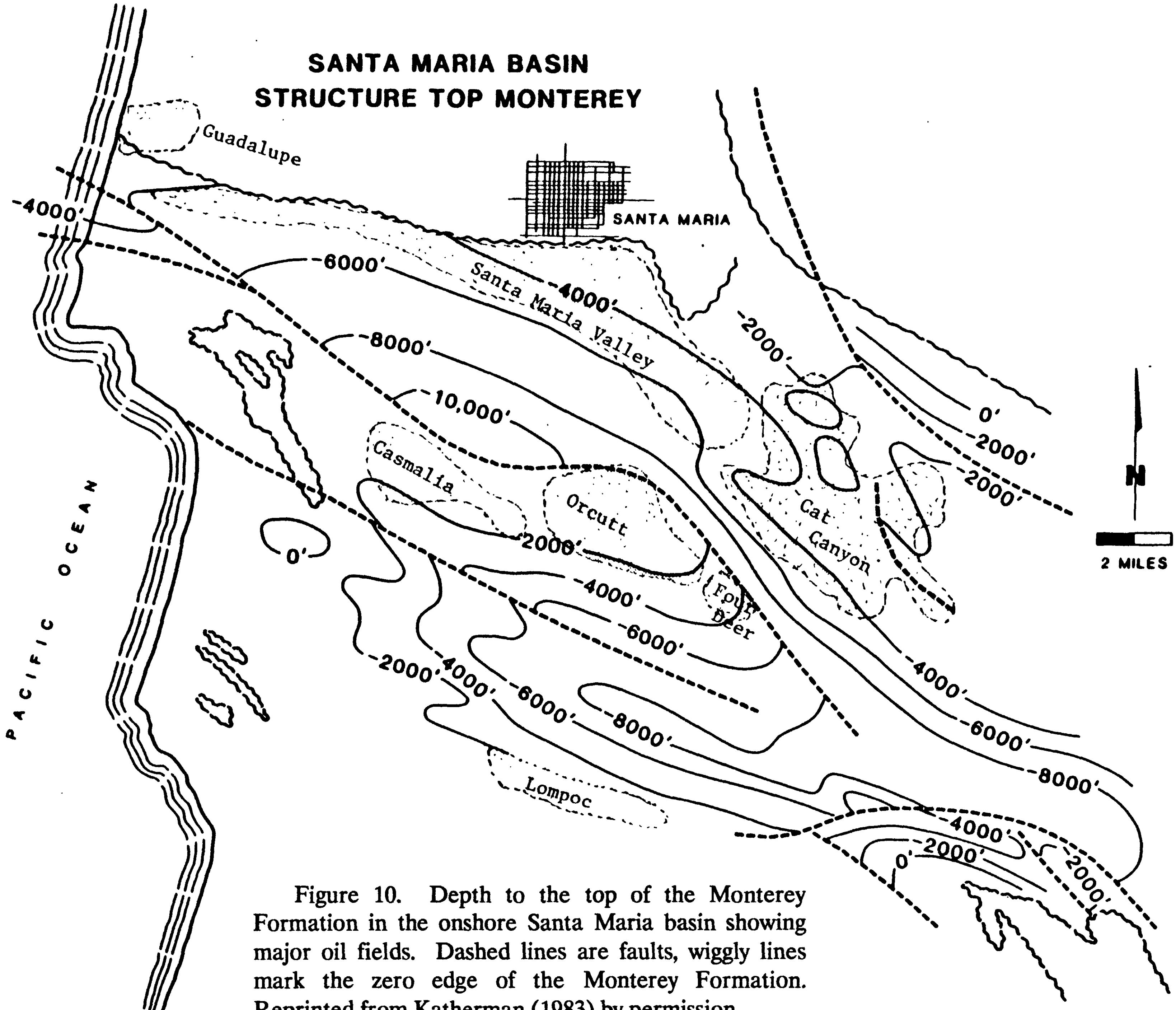


Figure 10. Depth to the top of the Monterey Formation in the onshore Santa Maria basin showing major oil fields. Dashed lines are faults, wiggly lines mark the zero edge of the Monterey Formation. Reprinted from Katherman (1983) by permission.

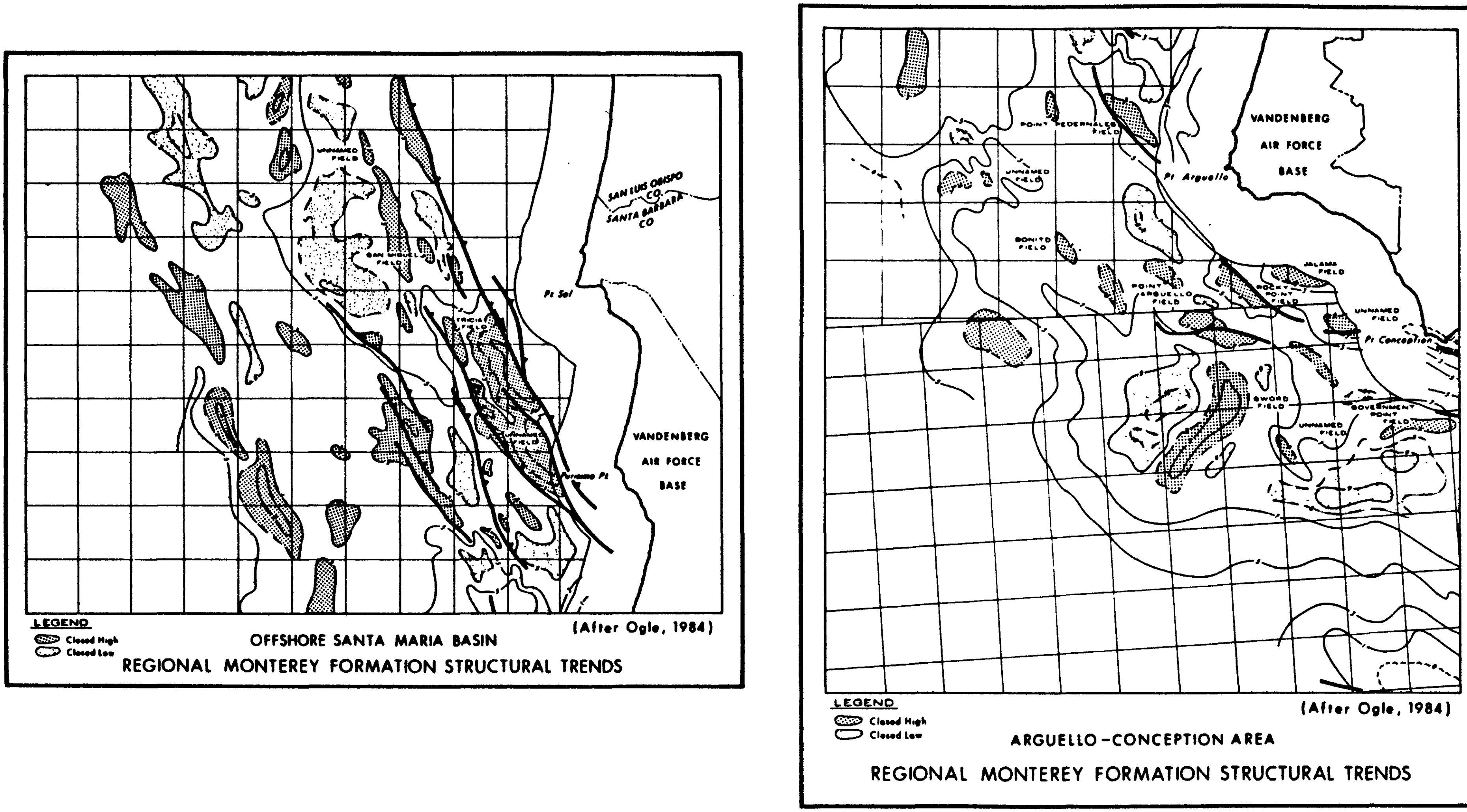


Figure 11. Generalized Monterey structure contour map of offshore Santa Maria basin (left) and Arguello-Conception area (right) showing oil and and gas fields. Contour interval is 2000 ft (except for dashed lines at 1000 ft to show boundaries of closed structural highs and lows), datum is sea level. The uncountoured area adjacent to the coastline is state waters. Reprinted from Ogle and others (1987) by permission.

Arroyo Grande fields, and the deepest average reservoir depths are in West area of the Cat Canyon field (see Table 1). However, most fields in the assessment province are rather complex and have a variety of oil zones and reservoir horizons (Table 3). Several of the more recently discovered pools and minor fields (not listed in the Nehring data base; see Table 3) have average depths of 7500 ft or more, including the Monterey deep pool in the Main area of the Orcutt field (av 9295 ft), Los Alamos field (av 9300 ft), and Careaga Canyon field (Old area av 7960 ft, San Antonio Creek area av 8400 ft).

Exploration status

History

Oil was first discovered in the assessment area in 1901, in the Main area of the Orcutt field, with cumulative production (through 1983) of 160.7 MMbbl (Tables 1-3). Ensuing exploration discoveries came rapidly, with 5 more major oil fields, mainly anticlinal traps, discovered by 1910. These were (with cumulative production through 1983): Lompoc (Main area, 42.8 MMbbl), 1903; Casmalia (36.8 MMbbl), 1905; Arroyo Grande (Tiber area, 5.3 MMbbl), 1906; West Cat Canyon (138.2 MMbbl), 1908; and East Cat Canyon (28.9 MMbbl), 1909. The Gato Ridge area of the Cat Canyon field (with cumulative production through 1983 of 39.6 MMbbl) was discovered in 1915 and a new pool in the Casmalia field in 1916. Due to poor marketing conditions, especially for the heavy oil produced in the area, little development occurred in the 1920s, and many wells in the area were shut in (Woodring and Bramlette, 1950). Discoveries in the 1920s included only the Huasna field (Tar Spring area, 0.01 MMbbl) in 1928, and Oak Park area (0.8 MMbbl) of Arroyo Grande field in 1929.

Even by the late 1910s, however, exploration for stratigraphic traps was underway, and with the use of reflection seismographs this search was finally rewarded by the discovery of the Santa Maria Valley field in 1934 (Canfield, 1939; Woodring and Bramlette, 1950), one of the largest fields in the assessment province with cumulative production (through 1983) at 151.3 MMbbl (Table 3).

Reconditioning of many wells during the 1930s and full production and further development during World War II resulted in a number of new field and area discoveries. These were (with cumulative production through 1983): the Careaga area (0.02 MMbbl) of Orcutt field, 1937; Houk area (10.6 MMbbl) of Santa Maria Valley, 1941; Zaca field (24.7 MMbbl), 1942; Barham Ranch field (Old area, 0.2 MMbbl), 1943; Olivera Canyon field (6.1 MMbbl), 1944; Sisquoc area (47.9 MMbbl) of Cat Canyon field, 1944; Tinaquaic area (0.07 MMbbl) of Cat Canyon field, 1945; Four Deer field (1.2 MMbbl), 1947; Guadalupe field (32.8 MMbbl) and Jesus Maria field (0.2 MMbbl), 1948.

Since the 1940s, discoveries have been more modest. During the 1950s were two new area discoveries: West area of Santa Maria Valley field (1.7 MMbbl) in 1953, and Central area (8.7 MMbbl) of Cat Canyon field in 1956. During the 1960s and early 1970s was discovery of the Lopez Canyon field (0.002 MMbbl) in 1963, LaVoie-Hadley area of the Huasna field (0.02 MMbbl) in 1965, Clark area (7.0 MMbbl) of Santa Maria Valley field in

1968, Bradley area (16.6 MMbbl) of Santa Maria Valley field in 1972, Los Alamos field (0.1 MMbbl) in 1972, and Careaga Canyon field (Old area, 0.05 MMbbl) in 1976. Very active exploration during the late 1970s and early 1980s spurred several new area discoveries, the most important of which (at the time of the assessment in 1987) were the San Antonio Creek area of Careaga Canyon field in 1983, Northwest area of the Lompoc field in 1983, and La Laguna area of the Barham Ranch field in 1983.

Future potential

Future resource potential in the area is highest in the undrilled state waters. Here, several of the fields discovered in federal offshore waters (but not in the reserve base of the assessment) lie partly in state waters (Figure 11).

Within the onshore area, future resource potential is only fair. Promising (but modest) prospects include deep pools in both fractured and permeable sandstone reservoirs trapped by small faults and other structures throughout the onshore Santa Maria basin. Discoveries made (or announced) from 1979 to 1986 included three classed at the time as new fields (Sisquoc Ranch, Harris Canyon Northwest, Lompoc Northwest fields), three classed as new pools (Diatomite and Monterey Deep pools in the Main area of the Orcutt field, and the Careaga area of the Orcutt field), and about 15 field extensions throughout the onshore Santa Maria basin. Because exploration attention in other parts of the assessment province (such as the Huasna basin) during the 1980s did not result in discoveries, prospects in these areas seem likely to be fair to poor.

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Table 1. Oil field data for the Santa Maria basin assessment province, based on Nehring data base through 1983 (NRG Associates, 1984).

Field	Trap type	Formation	Average Depth to top (ft)	Average Thickness (ft)	Average API Gravity	Disc'y Year	Cumulative prod'n + reserves Oil (MMbbl)	NGL (MMbbl)	Gas (Bcf)
Santa Maria Valley – Main*	Combination	Monterey	3330	3065	15	1934	228.0	19.4	234.0
Orcutt – Main area	Structural	Monterey	1700	1550	23	1901	176.0	18.6	261.6
Cat Canyon – West area	Combination	Monterey	6000	1500	15	1908	152.0	9.7	127.5
		Sisquoc	2800	600	17				
Cat Canyon – East + Gato Ridge	Combination	Monterey	3800	300	13	1909	95.0	3.4	45.0
		Sisquoc	2000	250	18				
Cat Canyon – Sisquoc area	Combination	Sisquoc	2750	1070	9	1944	70.0	2.2	28.5
Guadalupe	Combination	Sisquoc	2700	400	12	1948	48.0	2.1	25.5
Lompoc	Structural	Monterey	2250	500	20	1903	45.0	3.6	48.0
Casmalia	Structural	Monterey	700	1275	10	1905	45.0	1.8	21.9
Zaca	Structural	Monterey	3500	1700	8	1942	32.5	–	2.9
Cat Canyon – Central area	Stratigraphic	Sisquoc	2800	45	13	1956	10.5	–	4.2
Santa Maria Valley – West area	Stratigraphic	Monterey	4410	200	14	1953	8.5	0.7	9.0
		Foxen	3490	440	17				
Arroyo Grande – Tiber area	Combination	Pismo	750	300	15	1906	7.5	–	<0.1
Olivera Canyon	Structural	Monterey	3000	1500	10	1944	7.4	–	<0.1
Four Deer	Combination	Monterey	4800	980	30	1947	2.0	–	3.9
AVERAGE			2987	922	15	1929	66.2	4.4	58.0
TOTAL							927.4	61.5	812.0

* Includes Main, Southeast, Bradley, and Clark areas

Table 2. Cumulative production + reserves in small fields and field areas not included in the Nehring data base (NRG Associates, 1984). From California Division of Oil and Gas (1984, 1986), see also Table 3.

Field	Cumulative production + reserves	
	Thru 1985	Thru 1983
Arroyo Grande – Oak Park area	0.83	0.81 *
Los Alamos	0.47	0.14 *
Jesus Maria	0.39	0.38
Careaga Cyn	0.38	0.05
Barham Ranch	0.26	0.22
Cat Canyon – Tinaquaic area	0.07 **	
Orcutt – Careaga area	0.04 *	0.02 *
Huasna	0.03	0.03
Harris Canyon Northwest	0.006	–
Sisquoc Ranch (abd)	0.006	0.006
Lopez Canyon	0.002	0.002
Santa Maria Valley – North area (abd)	0.001	0.001

* Reserves not included.

** Production from Conservation Committee of California Oil Producers (1986).

Table 3. Oil field data for Santa Maria basin assessment province (from California Division of Oil and Gas, 1974, 1984).

Field / Area / Pool	Pool Disc'y Date	Cumulative production Oil (MMbbl)	Cumulative production Gas (Bcf)	Trap Type	Average Reservoir Depth (ft)	Average Reservoir Thickness (ft)	Pool API gravity
CAT CANYON		269.3	149.4				
EAST AREA		28.9*		Faulted homocline; lenticular sands			
Sisquoc	1953				3000	250	18
Brooks	1909				2100	200	10
Monterey	1953				3000	500	6
CENTRAL AREA		8.7*		Sand pinchout on homocline			
Sisquoc	1956				2800	45	13
SISQUOC AREA		47.9*		Permeability barrier on west flank of anticline			
Sisquoc	1944				2750	500	10
Thomas	1954				4900	70	7
Monterey	1944				4000	500	9
WEST AREA		138.2*		Faulted anticline; sand pinchout			
Sisquoc	1908				2800	600	17
Alexander	1953				3750	200	23
Los Flores	1938				6000	1500	15
GATO RIDGE AREA		39.6*		Faulted anticline			
Sisquoc	1937				2210	200	14
Monterey	1915				3800	300	13
TINAQUAIC AREA		0.07*		Anticline			
Monterey	1945				2020–3180	1200–3200	6
OLIVERA CANYON AREA		6.1*		Anticline			
Cherty – bent brown	1979				3000	1200	10
Buff and brown	1944				4000	300	10

Field / Area / Pool	Pool Disc'y Date	Cumulative production Oil (MMbbl)	Cumulative production Gas (Bcf)	Trap Type	Average Reservoir Depth (ft)	Average Reservoir Thickness (ft)	Pool API gravity
SANTA MARIA VALLEY		187.2	245.1				
MAIN AREA		151.3	224.4	Faulted homocline on north flank of syncline			
Foxen–Sisquoc	1934				2000	200	17
Santa Margarita	1938				3330	75	12–17
Arenaceous	1938				3360	180	12–17
Cherty	1937				3540	250	12–17
Bentonitic brown	1936				3800	200	12–17
Buff and brown	1936				4000	190	12–17
Dark brown	1936				4190	140	12–17
Oil sand	1936				4330	180	16
Siltstone & shell	1937				4520	1850	15
BRADLEY AREA		16.6	10.9	Fault trap on north flank of syncline			
Basal Sisquoc	1972	16.2	10.8		5560	170	14–17
Monterey	1972	0.51	0.14		5610	295	14
CLARK AREA		7.0	1.9	Faulted homocline with stratigraphic variations			
Foxen	1974	<0.0005	<0.001				
Basal Sisquoc	1970	0.14	0.01		5035	575	8
Monterey	1968	6.8	1.9		6725	850	9
NORTH AREA (abd)		0.001	<0.001	Unknown			
Foxen	1965				2250	340	13
HOUK AREA		10.6	5.2	Faulted nose with stratigraphic variations			
Foxen	1977	0.001	<0.001				
Basal Sisquoc	1941	5.9	3.8		4480	105	9
Houk	1952	4.5	1.2				
Monterey chert	1956	0.24	0.16		6385	1010	11
WEST AREA		1.7	2.7	Stratigraphic trap			
Foxen	1953				3490	160	14
Sisquoc	1953				3610	280	19

Field / Area / Pool	Pool Disc'y Date	Cumulative production Oil (MMbbl)	Cumulative production Gas (Bcf)	Trap Type	Average Reservoir Depth (ft)	Average Reservoir Thickness (ft)	Pool API gravity
Monterey	1953				4410	200	14
Knoxville	1953				4660	10–300	14
ORCUTT		160.8	276.2		1700	950	14–17
MAIN AREA		160.7	276.2	Faulted dome			
Diatomite	1979	0.004	<0.001				
Monterey	1901				1700	950	14–17
Arenaceous	1901				1700	175	14–17
Cherty	1905				1850	175	14–17
Bentonitic brown	1905				2100	200	19–23
Buff and brown	1905				2300	200	19–23
Dark brown	1905				2500	200	19–23
Point Sal	1905				2700	550	22–24
Oil sand	1905				2700	300	23–29
Siltstone & shell	1905				3000	300	23–29
Monterey deep	1981	0.09	0.19		9295	400	32–36
CAREAGA AREA		0.023	0.006	Faulted anticlinal nose			
Monterey	1937				5020	1040	22–34
CASMALIA		36.8	14.5	Faulted asymmetrical anticline			
Monterey	1905				700	1275	8–23
Point Sal	1916				2750	500	10
Lospe	1946				3953	345	22
LOMPOC		42.8	45.9				
Monterey	1903			Faulted asymmetrical anticline	2250	500	15–24
GUADALUPE		32.8	20.4	Faulted homocline			
Sisquoc	1948				2700	120	8–14
Monterey–Point Sal	1955				3000	200	12
Sisquoc–Monterey							
ZACA		24.7	2.9	Faulted homocline on south flank of anticline			

Field / Area / Pool	Pool Disc'y Date	Cumulative production Oil (MMbbl)	Cumulative production Gas (Bcf)	Trap Type	Average Reservoir Depth (ft)	Average Reservoir Thickness (ft)	Pool API gravity
Monterey	1942				3500	1700	8
FOUR DEER		1.2	2.7	Faulted anticlinal nose; stratigraphic variations			
Monterey	1947						
Arenaceous	1947				4800	100	35
Cherty	1947				5000	80–400	30
Bentonitic brown	1947				5600	80–350	27
Buff and brown	1947				5900	250–600	27
BARHAM RANCH		0.22	<0.001	Faulted anticline			
Basal Sisquoc	1945				1400	500	14
Monterey							
Arenaceous & cherty	1943				2800	200	15
JESUS MARIA		0.23	0.005	Homocline with permeability barriers			
Monterey							
Buff and brown	1948				2600	290	12
Dark brown	1952				2900	500	11
LOS ALAMOS		0.14	0.08	Faulted anticline			
Monterey	1972				9300	550	34
CAREAGA CANYON		0.05	0.001				
OLD AREA		0.05	<0.001				
Monterey	1976				7960	690	34
SAN ANTONIO CRK AREA		0.002	0.001				
Monterey	1983				8400	235	34.9
SISQUOC RANCH		0.006	<0.001				
Monterey	1980				1900	150	11–16
ARROYO GRANDE		6.1	0.04				
OAK PARK AREA		0.81	0.03	Faulted homocline on north limb of syncline			
Pismo							
Martin	1929				2890	50	15

Field / Area / Pool	Pool Disc'y Date	Cumulative production Oil (MMbbl)	Cumulative production Gas (Bcf)	Trap Type	Average Reservoir Depth (ft)	Average Reservoir Thickness (ft)	Pool API gravity
Elberta	1930				3100	50	14
TIBER AREA		5.3	0.01	Homocline on north limb of syncline			
Pismo							
Dollie	1906				750	300	15
Martin	1908				2000	100	13
Elberta	1908				2500	100	13
HUASNA		0.03	<0.001				
LAVOIE-HADLEY AREA		0.02	<0.001	Anticline			
Santa Margarita	1965				750-1560	500-1300	9
TAR SPRINGS AREA (abd)		0.01	<0.001	Anticline			
Monterey	1928				2085-3015	110	18
LOPEZ CANYON (abd)		0.002	<0.001	Faulted nose	2500	140	15
Point Sal	1963						

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