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TECTONIC CONTROLS ON PETROLEUM OCCURRENCE IN CENTRAL CALIFORNIA

ABSTRACT

Although wrench tectonics of the San Andreas transform fault system dominates the structure of modern central coastal California, regional sedimentary-basin evolution and petroleum geology are best viewed in the context of transform tectonics superposed on an older convergent-margin regime. Convergence along the central California margin continued from the Mesozoic until the mid-Tertiary, interrupted briefly in earliest Tertiary time by strike-slip faulting related, perhaps, to oblique subduction. Convergence finally ceased in the Oligocene, with the diachronous propagation of the San Andreas marginal transform system. Apparently, the locus of shear within the transform system migrated shoreward and continentward with time to the present position of the San Andreas fault, progressively involving granitic basement in lateral translations.

Regional tectonics strongly controls the character of central California sedimentary basins and the distribution of sedimentary facies. The expansive patterns of Cretaceous and earliest Tertiary forearc-basin sedimentation, less favorable in reservoir provenance, organic source-rock character, and burial history, were replaced in early Tertiary time by deposition in localized borderland basins related to strike-slip faults. However, it was the full development of the marginal transform system during the Neogene which provided the requisite elements for a productive and still prospective petroleum province: discrete, moderate-sized, structurally controlled sedimentary basins; deposition through rapid subsidence of thick piles of organic-rich marine sediments in silled, periodically anoxic borderland basins; favorable reservoir provenance through deep dissection of granitic uplifts; and extensive, early wrench-tectonic structuring of basin fill, often influencing syntectonic patterns of sedimentation.

INTRODUCTION

Petroleum was first commercially produced in California in 1876 (California Division of Oil and Gas, 1984). Soon thereafter, oil was found in many California sedimentary basins, and quickly, central California was established as one of the major petroleum provinces of the United States. Were Kern County (county seat in Bakersfield, Fig. 3-1) a state, it would rank fourth in annual production in the United States behind the production of Texas, Alaska, and Louisiana (California Division of Oil and Gas, 1984). In view of the economic importance of the resource, it is especially important to look beyond the statistics to the factors that conspire to give central California its stature as a petroleum-producing province. A quick look at the distribution of known major oil and gas accumulations in the region (Fig. 3-1) reveals that the answer is not simple. One immediately asks why gas and oil accumulations are nearly mutually exclusive in the Great Valley basin, with oil largely confined to the San Joaquin sub-basin and unassociated dry gas present mainly in the Sacramento sub-basin. Why does a large basin like the Salinas basin contain only one major field, while the smaller Santa Maria field houses many? Finally, why are the staggering oil reserves of the region contained

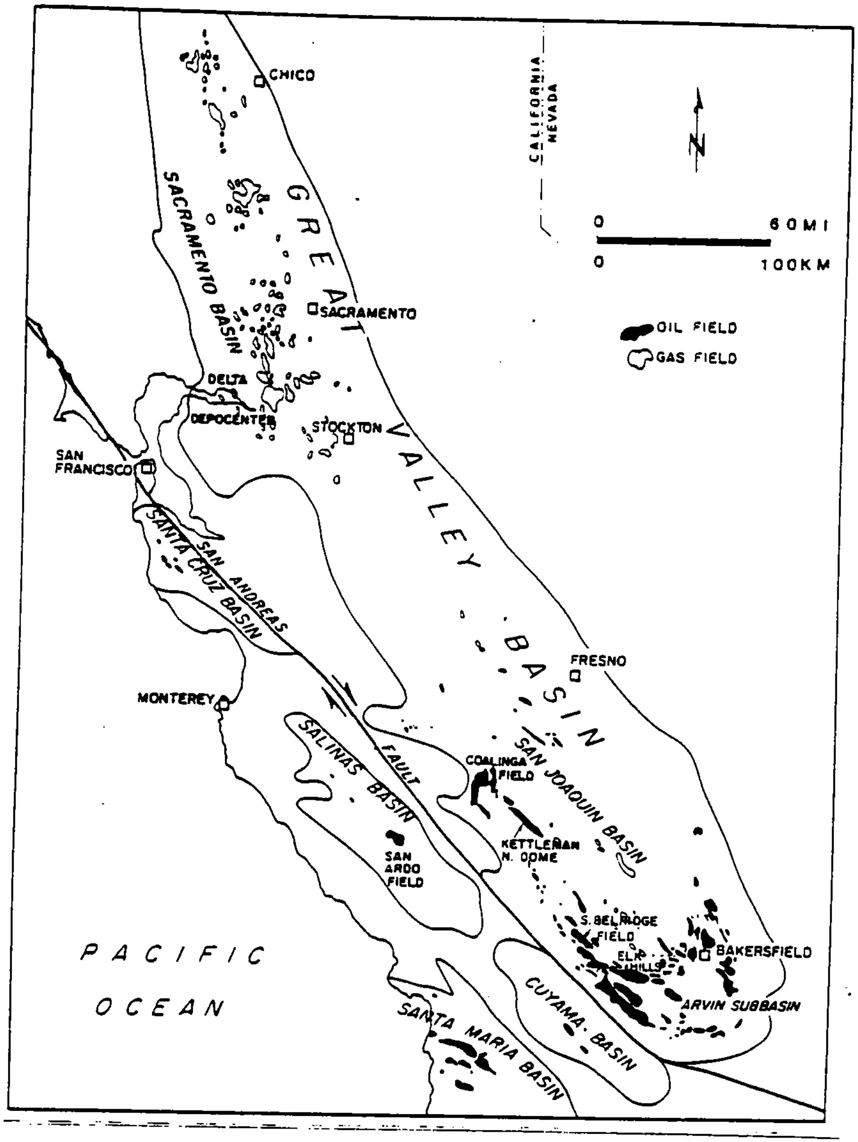


Fig. 3-1. Distribution of oil and gas fields of central California (modified from Munger, 1981). Basin outlines define general limits of thick upper Cenozoic sediment accumulations. Distribution of Paleogene and upper Mesozoic sediments differs somewhat, especially west of the San Andreas fault, as discussed in the text.

in Tertiary strata (9.8 billion barrels cumulative production plus reserves for the 10 largest fields in the region), whereas Mesozoic and lower Tertiary rocks contain a relatively modest amount of unassociated dry gas (10.2 trillion cubic feet in the 10 largest fields; statistics from California Division of Oil and Gas, 1984)?

As thorny as these questions seem, in their answers lies an elegant story of interacting geologic factors. Key, but varying through time in their importance, are structural style, depositional style, heat flow, paleobathymetry, paleoceanography and paleoclimate, sediment dispersal and provenance, and biologic response to paleoenvironment. Many of these factors are interrelated, sometimes in feedback systems; others are independent. What emerges from the analysis, however, is a demonstrable fundamental control on petroleum occurrence imposed by tectonic setting.

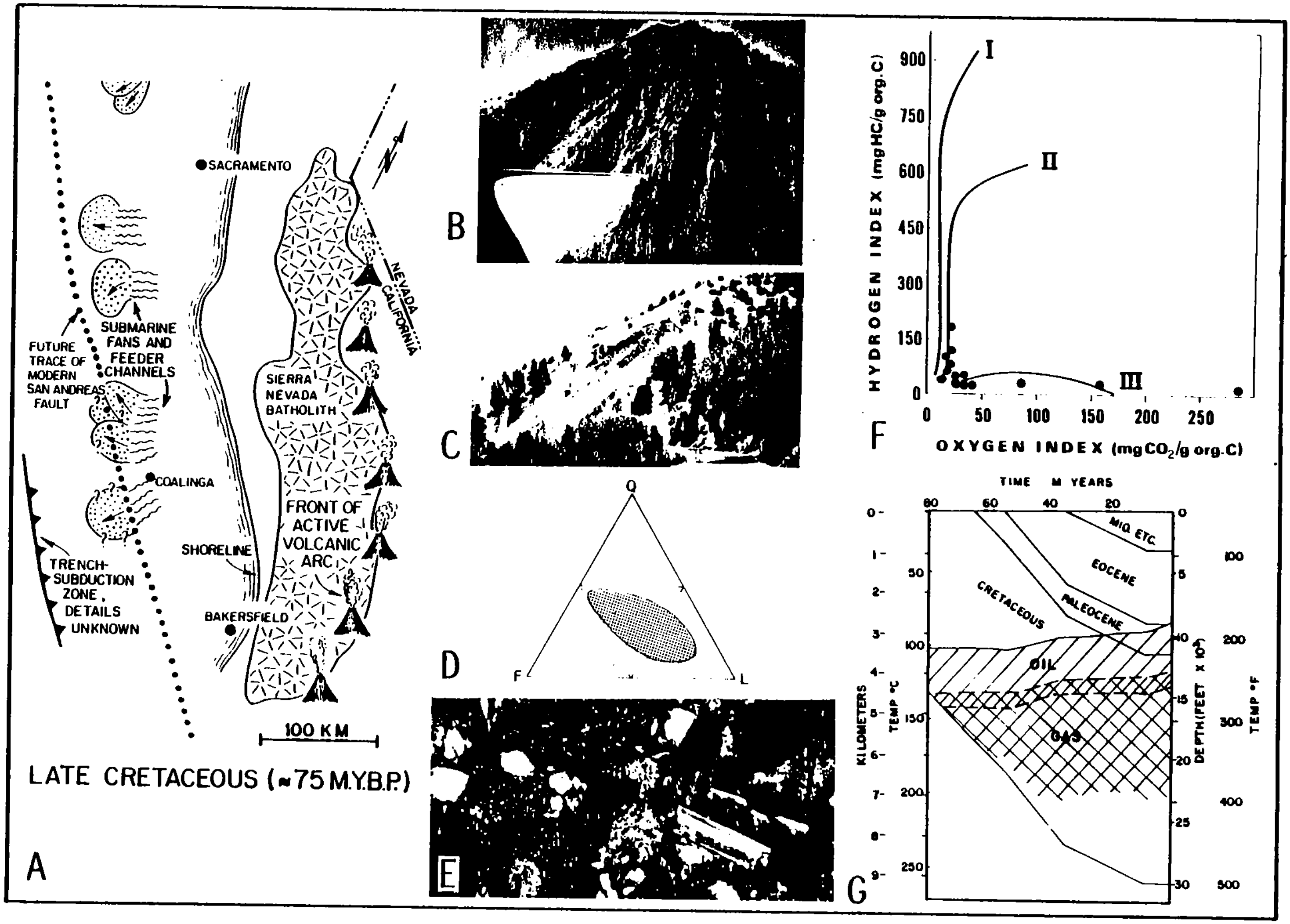
The balance of this paper reviews, at the expense of local detail, principal elements contributing to the habitat of petroleum during each of the three major tectonic episodes that characterized the later Mesozoic through Neogene sedimentary basins of central California. Somewhat more detailed regional syntheses of stratigraphy, paleogeography, and basin history of the central California region have been published in recent years by Bandy and Arnal (1969), Foss (1972), Dibblee (1973b), Nilsen and Clarke (1975), Blake *et al.* (1978), Graham (1978), Dickinson *et al.* (1979), and Lagoe (1984), among others.

LATE MESOZOIC TECTONIC REGIME

The consensus view of the past two decades of geologic study (see Dickinson and Seely, 1979) indicates that a north-south-trending continental-margin arc-trench system existed in central California during the Late Jurassic and Cretaceous (Fig. 3-2a). This system was established sometime after 150 my B.P. upon a predecessor arc-trench system, whose incompletely understood history may include a mid-Jurassic collision with a migratory oceanic arc (Schweickert and Cowan, 1975). After this collisional tectonic event (the Nevadan orogeny), a major sedimentary basin, the Great Valley basin, was established in the forearc region (Fig. 3-2), probably atop a block of backarc oceanic crust trapped continentward of a newly created subduction zone after the Nevadan collision (e.g., Fig. 3 of Ingersoll, 1982a). Once established, the Great Valley forearc basin persisted for about 85 my from Tithonian through Maastrichtian as a longitudinally continuous, deep-marine basin some 700 km in length. Oceanward from the basin lay a subduction zone, now represented by rocks of the Franciscan Complex, whose accretionary wedge achieved sufficient bathymetric relief to maintain the Great Valley basin as a ponded, unfilled, deep-marine forearc (Ingersoll, 1976, 1979; Dickinson and Seely, 1979). The Cretaceous history of sediment accumulation in the basin apparently consists largely of passive filling of the basin with deep-sea-fan and related sediments with attendant isostatically induced subsidence (Dickinson *et al.*, this volume).

The general pattern of sedimentation is well understood, through many years of investigation of outcrops around the basin margins (notably Ingersoll, 1976, 1979) and through exploratory drilling for gas (Cherven, 1983c). Deep-sea fans (Fig. 3-2b), longitudinally deployed but transversely fed from the Sierra Nevada arc terrane (Fig. 3-2a), accumulated with thick interleaved hemipelagic muds (Fig. 3-2c) from Late Jurassic through Campanian time. Shallow-marine equivalents occupied a narrow tract along the eastern part of the basin (Fig. 3-2a). The basin widened through time, with the continentward migration of arc magmatism and the oceanward migration of the trench as the accretionary wedge expanded (Ingersoll *et al.*, 1977).

Fig. 3-2. Elements of the late Mesozoic tectonostratigraphic regime: (a) Generalized paleogeography and sediment dispersal, Great Valley forearc basin (modified from Graham, 1981). (b) Thick channelized mid-fan sandstone sequence encased in basin-plain/slope shales above (to right) and below (barely visible on lower hill slope above dam) in Turonian strata exposed 55 km west of Sacramento; Sandstone package is 600 m thick. (c) Thick basin-plain shale sequence of Cenomanian age exposed 65 km northwest of Sacramento. (d) QFL framework composition of upper Mesozoic sandstones of the Great Valley basin (Ingersoll, 1983) and the Salinian block (Graham, 1976a); shaded area represents field occupied by 241 modal analyses. (e) Photomicrograph of a medium-coarse-grained Upper Jurassic sandstone from near the base of the Great Valley Group in the Sacramento basin. Note extreme compaction and deformation of dark, altered rock fragments, effectively occluding porosity and permeability. (f) Modified Van Krevelen diagram (Tissot and Welte, 1978) characterizing kerogen from the Great Valley Group; samples are from Jurassic through Campanian rocks exposed west of Sacramento. (g) Burial-history/petroleum-maturation diagram (Zieglar and Spotts, 1978) for the delta depocenter (Fig. 3-1).


A
LATE CRETACEOUS (≈75 M.Y.B.P.)
SACRAMENTO
COALINGA
BAKERSFIELD
SHORELINE
SIERRA NEVADA BATHOLITH
FRONT OF ACTIVE VOLCANIC ARC
NEVADA
CALIFORNIA
SUBMARINE FANS AND FEEDER CHANNELS
FUTURE TRACE OF MODERN SAN ANDREAS FAULT
TRENCH-SUBDUCTION ZONE, DETAILS UNKNOWN
100 KM
B
C
D
Q
F
L
E
F
HYDROGEN INDEX (mgHC/g org.C)
OXYGEN INDEX (mgCO2/g org.C)
I
II
III
0
150
300
450
600
750
900
0
50
100
150
200
250
G
TIME M YEARS
80
60
40
20
0
MIO ETC
EOCENE
PALEOCENE
CRETACEOUS
OIL
GAS
KILOMETERS
0
1
2
3
4
5
6
7
8
9
TEMP °C
50
100
150
200
250
DEPTH (FEET X 10³)
5
10
15
20
25
30
TEMP °F
100
200
300
400
500

Only near the end of the Cretaceous did the character of deposystems change markedly. In the Sacramento basin, fan facies were replaced in the Masstrichtian by periodically prograding deltaic deposystems (Cherven, 1983c), while the relatively clastic-starved San Joaquin basin displayed low-oxygen muddy slope deposystems (McGuire, 1984). This shoaling may simply reflect infilling of initial bathymetric relief in the forearc region. Alternatively, analysis of subsidence history seems to suggest that tectonic uplift, perhaps related to shallowing of the angle of subduction during the latest Cretaceous and early Tertiary, played a role in terminating fan sedimentation in extremely deep water (Dickinson *et al.*, this volume; Moxon, 1986).

Petrologic and paleocurrent studies demonstrate that coarse clastics of the Great Valley Group were derived from the Sierra Nevada and Klamath basement terranes (Ingersoll, 1983). In particular, the history of magmatism, deformation, and erosion of the Sierra Nevada arc is elegantly mirrored in petrofacies recognized in sandstones of the Great Valley Group (Dickinson and Rich, 1972; Ingersoll, 1978b; 1983; Mansfield, 1979; Schweickert, 1981). Although episodicity in arc volcanism is indicated by detrital modes of Great Valley sandstones, lithic-rich graywacke sandstones of the Upper Jurassic generally yield upward to increasingly arkosic compositions in the Campanian-Maastrichtian top of the Great Valley Group (Fig. 3-2d). This trend reflects the overall eastward migration of arc magmatism through time and the eventual dormancy of the arc in California during the Paleogene (Dickinson and Snyder, 1978; Ingersoll, 1978b).

Characteristics of the forearc basin imparted a moderately favorable habitat for the generation and accumulation of petroleum in Mesozoic strata of the Great Valley forearc basin. Lenticular geometries of turbidite and deltaic sandstone bodies yielded many stratigraphic and combination structural-stratigraphic traps in the Campanian-Maastrichtian section (California Division of Oil and Gas, 1973); deep-sea-fan facies in older strata likely offer similar possibilities, but have been little tested because of excessive depth of burial. Structural traps developed during the Mesozoic are relatively few and modest, however, as is typically the case for little-deformed forearc regions (Dickinson and Seely, 1979).

Mesozoic sandstones comprising potential reservoir sections were derived from the adjacent Sierran magmatic arc (Fig. 3-2a), and unfortunately, contain abundant volcanic rock fragments and feldspars that readily deteriorate with great burial through physical compaction and diagenesis (Fig. 3-2e). The result is greatly diminished porosity and permeability in all but the youngest, least buried, and most arkosic of Great Valley Group sandstones (see Fig. 4 of Zieglar and Spotts, 1978).

Maximum accumulations of Great Valley Mesozoic sediments approach 15 km (Ingersoll, 1979; Fig. 3-3, column 7), and although such thicknesses foster poor reservoir quality, they may also promote thermal maturation of organic matter contained in the sedimentary section. Zieglar and Spotts (1978) used Lopatin's (1971) technique to hindcast the maturation history of the Mesozoic-Tertiary section of the delta depocenter, northwest of Stockton in the Sacramento basin (Fig. 3-1). Their reconstruction (Fig. 3-2g) illustrates the tremendous thickness of Mesozoic strata (the base of the Upper Cretaceous is buried more than 10 km), and predicts that Mesozoic strata in that region are now generating thermogenic gas. However, their burial-history diagram, a plot of undecompacted rock accumulation, employed a geothermal gradient probably greater than that of the Mesozoic forearc basin. Modern forearc basins display among the lowest heat-flow values observed because of the relatively cold subducting slab that underlies the forearc region. Pyrolysis data shown in Fig. 3-2f represent a sample traverse through the entire thickness of the Great Valley Group outcrop west of Sacramento. These pyrolysis analyses, as well as unpublished visual kerogen analyses from the outcrop section and a deep-test well near Coalinga in the San Joaquin basin, all suggest that much of the Great Valley Group actually currently resides in the "oil window" or is even thermally immature with respect to significant hydrocarbon generation.

If indeed low heat flow in the Great Valley forearc retarded maturation of organic matter, and if, therefore, the dry gas produced from the Sacramento and northern San Joaquin basins is not thermogenic, then its origin lies instead in the nature of the organic matter contained in Mesozoic strata. This organic matter, apparently, is of several varieties (Fig. 3-2f). Oil-prone Type I and II kerogens (Tissot and Welte, 1978) are rare, occurring locally at the base of the sequence in Jurassic shaly rocks that predate the main progradation of deep-sea fans (based on work in progress), and more notably, in low-oxygen slope shales in the Moreno Formation (Fig. 3-3, column 6) at the top of the Cretaceous in the San Joaquin basin (McGuire, 1984). More common is hydrogen- and oxygen-depleted organic material that probably contributes little to petroleum generation. Most conspicuous, however, is terrestrially derived, Type III kerogen, introduced into the forearc basin with the voluminous turbidites of the Great Valley Group. Locally, such organic matter is sufficiently abundant to form lignitic beds in the deep-water sequence. Thus, the unassociated dry gas produced from Mesozoic forearc strata can be explained in terms of the nature of the organic material, rather than an extreme thermal history.

PALEOGENE TECTONIC REGIME

The longitudinal continuity and laterally extensive deposystems of the Great Valley forearc were disrupted in the early Tertiary with the tectonic emplacement of the granitic terrane of the Salinian block along a fault system widely termed the "proto-San Andreas fault" (Fig. 3-4a). The site of origin of this fragment of continental-margin-arc basement remains uncertain; current hypotheses debate an origin from the latitude of southern Mexico (Howell *et al.*, this volume) or from the interior of the southern end of the Sierran arc (Dickinson, 1983). In either case, Late Cretaceous–early Tertiary oblique subduction is the favored mechanism for the beginning of strike-slip emplacement of the Salinian block. The timing of the event, suggested by structural and stratigraphic relations in the Salinian block and the San Joaquin basin, is Late Paleocene, about 55 my B.P. (Graham, 1976a; Page, 1981; Howell *et al.*, this volume).

The accretion of the Salinian block forced a major reorganization of sedimen-

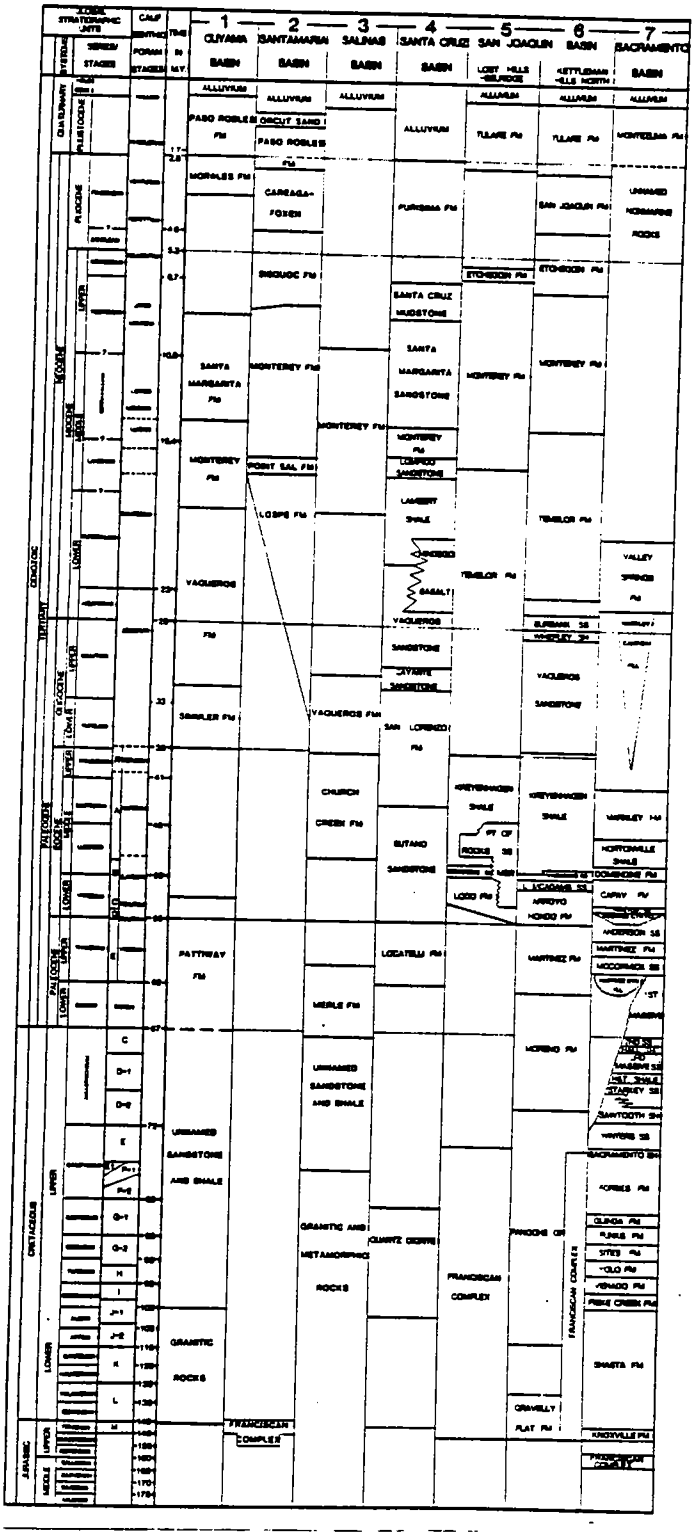
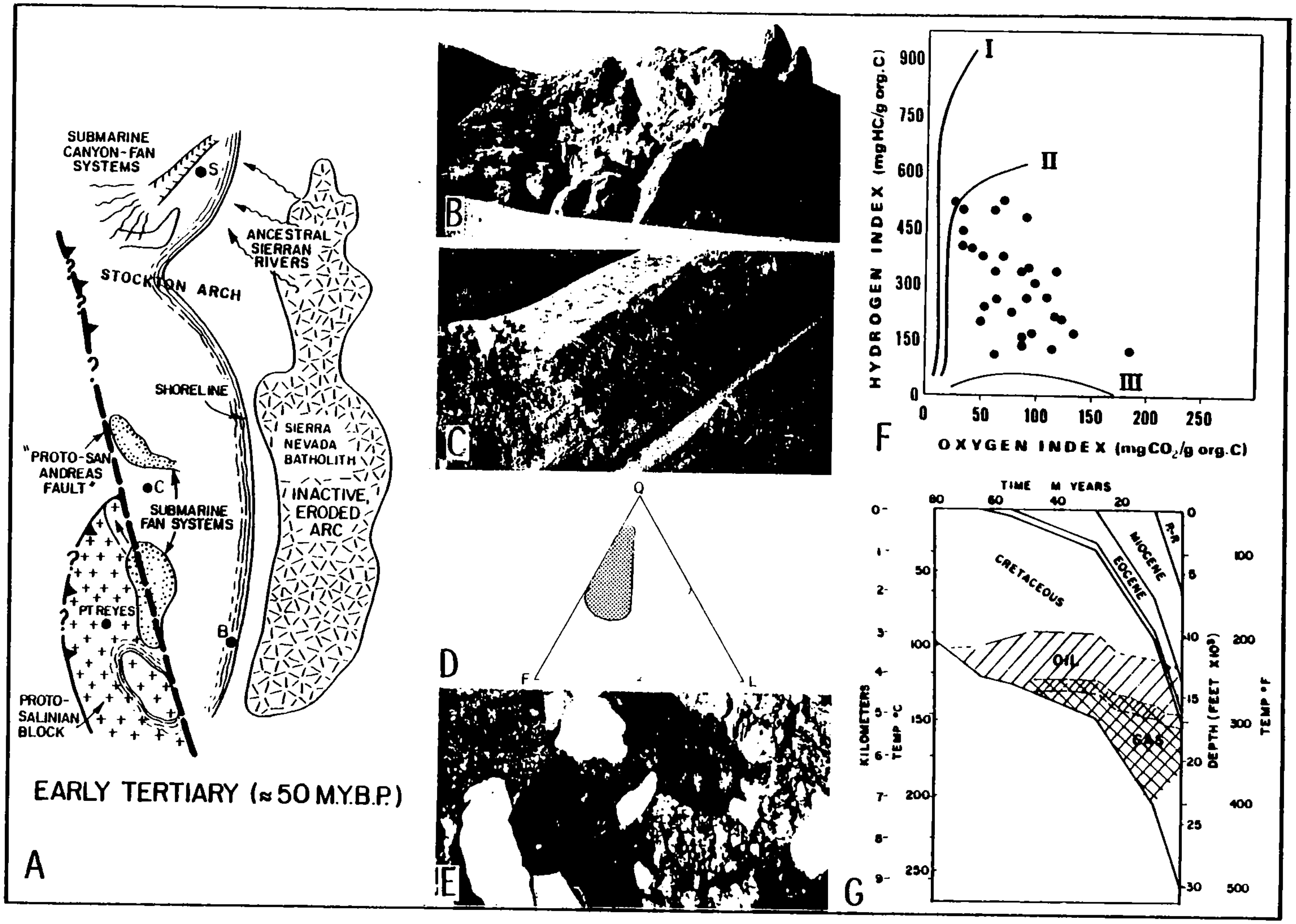


Fig. 3-3. Mesozoic and Cenozoic stratigraphic units of principal sedimentary basins of central California (simplified from Bishop and Davis, 1984a–c).

Fig. 3-4. Elements of the Paleogene tectonostratigraphic regime of central California: (a) Generalized paleogeography and sediment dispersal (modified from Dickinson *et al.*, 1979; Graham, 1981); B is Bakersfield, C is Coalinga, S is Sacramento. (b) Thick-bedded, amalgamated sandstone inner/mid-fan sequence of the Eocene Point of Rocks Formation (Fig. 3-3, column 5), exposed 10 km southwest of South Belridge oil field (Fig. 3-1); the sandy sequence is 900 m thick at this locality, with few shaly interbeds (Clarke, 1973). (c) Thick slope/basin-plain shale sequence of the Eocene Kreyenhagen Formation (Fig. 3-3, column 6) exposed 30 km southeast of Coalinga; shale is largely biosiliceous and well laminated. (d) QFL framework composition of Eocene sandstones from the San Joaquin basin (Clarke, 1973; Dickinson *et al.*, 1979; Graham and Berry, 1979; Bent, 1985) and the Salinas basin (Graham, 1976a); shaded area represents field occupied by 79 modal analyses. (e) Photomicrograph of coarse-grained sandstone from Lower Eocene reservoir at East Coalinga Extension oil field; dark grains are stained and altered potassium feldspar, light grains are quartz, mottled areas are diagenetic kaolinite. (f) Modified Van Krevelen diagram (Tissot and Welte, 1978) characterizing kerogen from the Eocene Kreyenhagen Formation of the San Joaquin basin; data are from Milam (1985) from samples from three wells, one 10 km south of Coalinga, one from 30 km northeast of Coalinga, and one from 10 km north of South Belridge oil field (Fig. 3-1). (g) Burial-history/petroleum-maturation diagram (Zieglar and Spotts, 1978) for the South Belridge region of the San Joaquin basin.


SUBMARINE CANYON-FAN SYSTEMS
S
ANCESTRAL SIERRAN RIVERS
STOCKTON ARCH
SHORELINE
SIERRA NEVADA BATHOLITH
INACTIVE, ERODED ARC
"PROTO-SAN ANDREAS FAULT"
C
SUBMARINE FAN SYSTEMS
PT REYES
B
PROTO-SALINIAN BLOCK
EARLY TERTIARY (≈50 M.Y.B.P.)
A
B
C
Q
F
L
D
E
HYDROGEN INDEX (mgHC/g org.C)
900
750
600
450
300
150
0
I
II
III
0
50
100
150
200
250
F
OXYGEN INDEX (mgCO2/g org.C)
TIME M YEARS
80
60
40
20
KILOMETERS
0
1
2
3
4
5
6
7
8
9
TEMP °C
50
100
150
200
250
CRETACEOUS
EOCENE
MIOCENE
P-R
OIL
GAS
DEPTH (FEET X10³)
0
5
10
15
20
25
30
TEMP °F
100
200
300
400
500
G

HAM FIG. R4

tary basins in central California. The forearc basin was bounded to the west by the locally emergent Salinian block, itself the foundation for several small, deep-water sedimentary basins comprising a Paleogene continental borderland (Fig. 3-4; Nilsen and Clarke, 1975). The forearc basin was segmented into the Sacramento basin and the San Joaquin basin with the growth of the transverse Stockton arch (Fig. 3-4a; Dickinson, *et al.*, 1979). North of the arch, the Sacramento basin was a shelved forearc during the Paleogene, and the site of episodic transgressions and regressions with attendent cutting of several major submarine canyon systems (Fig. 3-3, column 7; Almgren and Hacker, 1984). A large portion of the San Joaquin segment of the forearc basin remained a deep-marine basin as the eastward extension of the Paleogene borderland. Deep-sea fans prograded into the San Joaquin basin (Fig. 3-4a), fed from the granitic basement terranes of the Sierra Nevada and Salinian block (Clarke and Nilsen, 1973); Nilsen and Clarke, 1975; Graham and Berry, 1979). These clastic deposystems of the Paleogene borderland differed markedly from their Mesozoic Great Valley predecessors in being areally restricted, remarkably sand-rich, and lacking in distal, outer-fan/basin-plain facies (Fig. 3-4b). This new style of fan sedimentation is probably due largely to the small, steep-sided, structurally controlled nature of borderland basins, but it may have been further enhanced by the nature of detritus availabe in source terranes. Granitic rocks were widely exposed in the tectonized Salinian block, and the granitic rocks of the Mesozoic Sierran arc were laid bare by erosion during more than 3 my of arc inactivity with low-angle subduction during the Laramide orogeny (Dickinson and Snyder, 1978). Furthermore, intense weathering in the tropical climes of the Eocene (e.g., Bateman and Wahrhaftig, 1966) and widespread development of high-energy shallow-marine deposystems in the Great Valley basin (Nilsen and Clarke, 1975; Harun, 1985) yielded relatively mature quartzofeldspathic sediment (Figs. 3-4d and e).

The lenticular geometries of shallow-marine sandstones like the Gatchell Sandstone (= Lower McAdams in Fig. 3-3, column 6) on Coalinga anticline, and truncations and pinch-outs associated with Paleogene submarine canyons in the Sacramento basin (Almgren and Hacker, 1984) produced spectacular stratigraphic traps. Modest structuring occurred during the Paleogene (Harding, 1976), thus assisting in trapping, but its character remains poorly defined. Unfortunately, the attractiveness of Eocene sandstones as proven and potential reservoirs is diminished by depth of burial in many areas (Fig. 3-4g). Aside from porosity loss with burial compaction (Fig. 3-3 of Zieglar and Spotts, 1978), kaolinitization of Eocene reservoirs is widespread (Fig. 3-4e). Attendent porosity loss has widely been attributed to burial diagenesis, and has even been suggested to contribute to trapping in fields near Coalinga (Schneeflock, 1978). Alternatively, kaolinitization of shallow-marine to nonmarine reservoirs may be related, at least in part, to surfacial weathering in the tropical Eocene climate, as observed in the Eocene fluvial Auriferous Gravels of the Sierra Nevada (Bateman and Wahrhaftig, 1966). In either case, Eocene rocks house volumetrically significant reserves in only a few locales. Paleocene and Oligocene rocks, not well represented in the stratigraphic record in central California, contribute even less to regional petroleum reserves.

Eocene rocks produce mostly dry gas in the delta depocenter of the

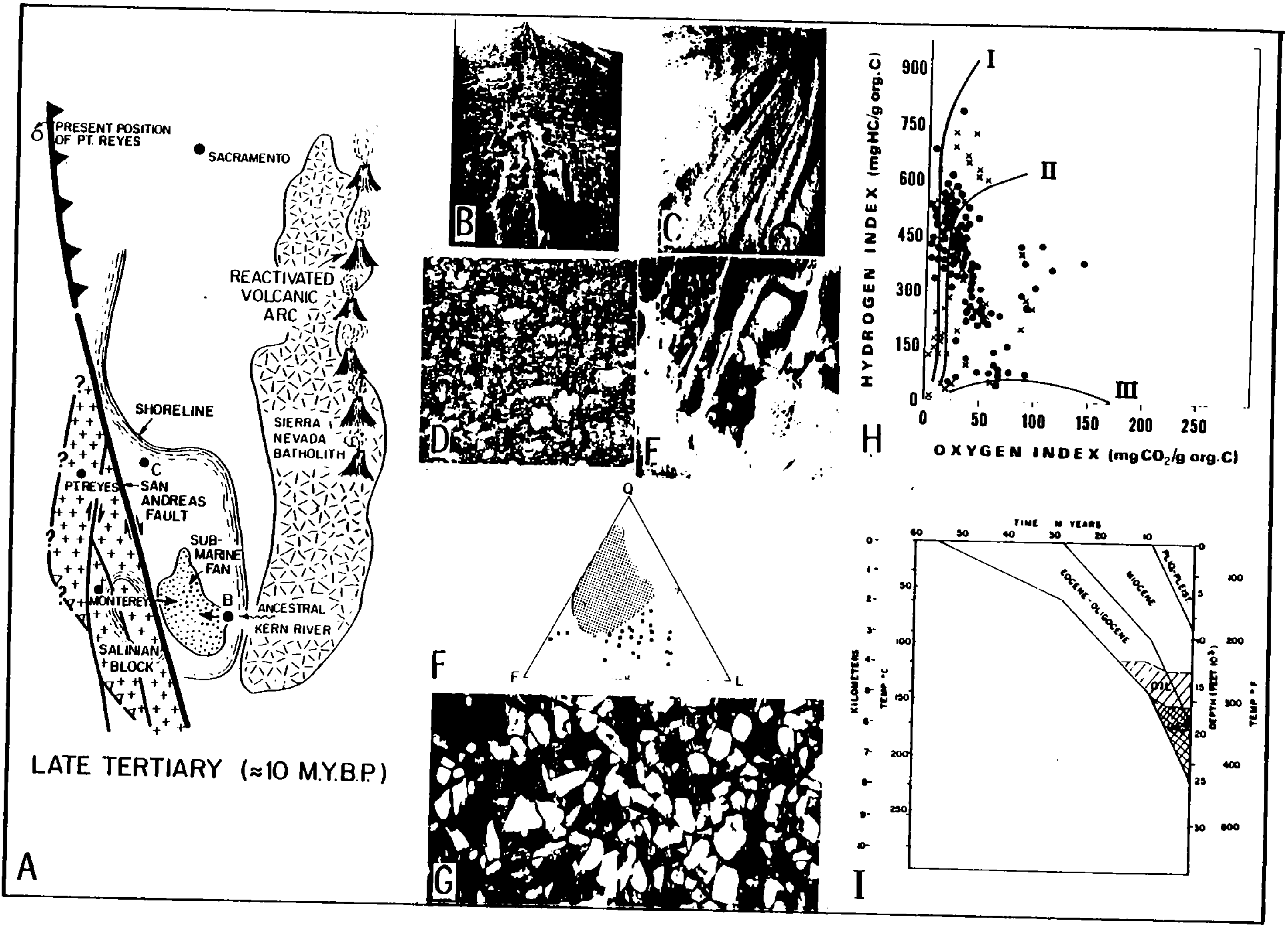
Sacramento basin, but in the San Joaquin and Santa Cruz basins. oil occurs (Fig. 3-1). In excess of half-a-billion barrels of oil occupied the Eocene stratigraphic trap at Coalinga anticline (California Division of Oil and Gas, 1984). Although it might be assumed that this Eocene-reservoired oil was sourced from the Miocene Monterey Formation, stratigraphic and structural relations, and the distribution of source-rock facies in the Monterey Formation (Graham and Williams, 1985) strongly suggest that most Eocene-reservoired oil in the San Joaquin basin was sourced from Eocene, or possibly, uppermost Cretaceous shales. The most likely candidate for the source is the Kreyenhagen Shale of the San Joaquin basin and its San Andreas-offset equivalent in the Santa Cruz Mountains, the San Lorenzo Formation (Fig. 3-3, columns 4–6). Both include thick phosphatis, well laminated intervals suggestive of low-oxygen environments (Stanley, 1984; Milam, 1985). These rocks may represent an anoxic, silled-basin setting in the San Joaquin basin, or simply the intersection of the oceanic low-oxygen water mass with slopes of the continental margin. The Kreyenhagen Formation in the northern San Joaquin basin, in particular, comprises a source-rock section 300–400 m thick (Fig. 3-4c) with total organic carbon (T.O.C.) commonly in the 2–5% range (Milam, 1985). Type II kerogen is widespread and abundant in these largely biocalcareous and biosiliceous rocks (Fig. 3-4f). The close spatial relationship between source rock facies of the Kreyenhagen and San Lorenzo Formations, and Eocene-reservoired oil supports the notion that the oil was sourced from Eocene rocks where sufficiently buried (Fig. 3-4g). Conversely, Eocene accumulations are absent in the Salinas basin, where Eocene shales represent well oxygenated basin-plain environments (Graham, 1976a).

NEOGENE TECTONIC REGIME

Subduction continued through the middle Tertiary in central California, with Oligocene-Miocene arc volcanism in the Sierra Nevada signaling the return to normal angles of plate descent (Dickinson and Snyder, 1978). Plate convergence was short-lived, however, because the interaction of the East Pacific Rise spreading center with North America resulted in the northwestward migration of the Mendocino triple junction and propagation of the San Andreas transform-fault system obliquely across the outer part of the former convergent-margin system in central California after about 20 my/B.P. (Fig. 3-5a; Atwater, 1970; Atwater and Molnar, 1973).

The structural impacts of the establishment of the San Andreas transform system are diverse and important. Initial effects seem to be a basin reorganization triggered by extension related to triple junction tectonics (Graham, 1976a, 1978; Dickinson and Snyder, 1979; Ingersoll, 1982b). The small, discrete basins shown in Fig. 3-1 assumed their general shapes and dimensions during this period. Localized occurrences of rhyolitic-basaltic volcanism (Fig. 3-3, column 4; Matthews, 1976; Dickinson and Snyder, 1978) and subsidence analysis (Graham and Williams, 1985; Dickinson *et al.*, this volume) support the notion of rift-like extension as a generative mechanism for these basins. This Early to Middle

Fig. 3-5. Elements of the Neogene tectonostratigraphic regime of central California: (a) Generalized paleogeography and sediment dispersal (modified from Graham and Williams, 1985); B is Bakersfield, C is Coalinga. (b) Nested sequence of lenticular 3- to 4-m-thick, shallow-marine-bar sandstones of the Temblor Formation (stratigraphic tops to right) exposed 30 km southeast of Coalinga (Fig. 3-3, column 6); this Middle Miocene sequence produces oil in many fields in the Coalinga area. (c) A small portion of the 3-km-thick Middle and Upper Miocene Monterey Formation (Fig. 3-3, column 5) exposed 10 km southwest of South Belridge oil field (Fig. 3-1); section consists largely of biosiliceous shale, porcelanite, and diatomite; circled human figure provides scale. (d) Photomicrograph of Middle Miocene calcereous mudstone from the Monterey Formation of the Salinas basin; white, medium-fine-grained sand-sized grains are foraminiferal tests, matrix is largely nannoplankton and clay pigmented by abundant organic matter. (e) S.E.M. photomicrograph of a sample from the Upper Miocene diatomite reservoir at South Belridge oil field. (f) QFL framework composition of Miocene sandstones from the San Joaquin (Bent, 1985) and Salinas basin (Graham, 1976a); shaded area represents field occupied by 123 modal analyses; scattered points represent lithic-rich Miocene sandstones of the San Joaquin basin. (g) Photomicrograph of quartzofeldspathic Middle Miocene sandstone from the Salainas basin retaining excellent porosity. (h) Modified Van Krevelen diagram (Tissot and Welte, 1978) characterizing kerogen from the Miocene Monterey Formation of the San Joaquin basin (dots, data from Graham and Williams, 1985) and the Salinas basin (crosses, data from Marion, 1986). (i) Burial-history/petroleum-maturation diagram (Zieglar and Spotts, 1978) for the Arvin subbasin of the southern San Joaquin basin (Fig. 3-1).


A
PRESENT POSITION OF PT. REYES
SACRAMENTO
REACTIVATED VOLCANIC ARC
SHORELINE
SIERRA NEVADA BATHOLITH
C
PT. REYES
SAN ANDREAS FAULT
SUB-MARINE FAN
MONTEREY
B
ANCESTRAL KERN RIVER
SALINIAN BLOCK
?
LATE TERTIARY (≈10 M.Y.B.P.)
B
C
D
E
F
Q
F
L
G
H
HYDROGEN INDEX (mgHC/g org.C)
OXYGEN INDEX (mgCO2/g org.C)
900
750
600
450
300
150
0
50
100
150
200
250
I
II
III
I
TIME M YEARS
60
50
40
30
20
10
KILOMETERS
TEMP °C
DEPTH (FEET 10³)
TEMP °F
EOCENE - OLIGOCENE
MIOCENE
PLIO-PLEIST
OIL
0
1
2
3
4
5
6
7
8
9
10
50
100
150
200
250
0
5
10
15
20
25
30
100
200
300
400
600

HAM FIG #5

Miocene pulse of subsidence engendered a highly favorable habitat for petroleum in Neogene rocks in central California by creating initially bathymetrically deep basins which filled with sediments during the Neogene.

Wrench-tectonic deformation of central California began in Middle Miocene with the development of through-going strike-slip faults, en-echelon folds, and local thrusts (Harding, 1976; Graham, 1978). These structures are best developed where basement consists of Mesozoic subduction complex, as discussed below. The wrench-fold belt flanking the San Andreas fault propagated eastward away from the fault with time (Harding, 1976). Neogene right slip on the San Andreas family of faults slivered and distended the Salinian block, and enhanced the borderland topography first developed in the Paleogene (Fig. 3-5a). Late in the Neogene, compressional or transpressional structures developed across central coastal California (Page, 1981). Their origin remains uncertain, but they may be a response to a slight change in pole of rotation between the Pacific and North American plates (Cox and Engebretson, 1985). Plio-Pleistocene high-angle reverse faults have been mapped in the Salinian block and western San Joaquin basin for many years, but recently published reflection-seismic profiles in the Coalinga-Kettleman region (Wentworth *et al.*, 1983) hint that late Neogene–Recent compressional structures may be more extensive than previously realized.

The Sacramento basin persisted as a forearc basin occupied by fluvial to estuarine deposystems (Fig. 3-3, column 7) during the Miocene (Dickinson and Seely, 1979; Graham *et al.*, 1984). South of the migrating triple junction, however, sedimentation continued concurrently with wrench structuring, initially in deep-marine basins, then succeeded by shallow-marine and nonmarine deposystems. As a result, local unconformities, stratal wedging, lenticular sandstone geometries are common. Most notable, perhaps, are sandstone bodies of the Upper Miocene Stevens deep-sea-fan complex of the San Joaquin basin (Fig. 3-5a; MacPherson, 1978; Webb, 1981). Some elements of the fan complex wrap around wrench anticlines that were growing and had sea-floor relief during turbidite deposition.

Neogene sandstones of central California are mostly feldspathic, except for some feldspathic-lithic sandstones of the San Joaquin basin derived from the waning Neogene Sierra Nevada arc (Bent, 1985; Fig. 3-5f). The compositional maturity of Neogene coarse clastics largely reflects the widespread exposure of granitic basement (Fig. 3-5a) and older arkosic sedimentary rocks. However, high-energy shallow-marine deposystems like the ancestral Kern River delta (Fig. 3-5a) in the San Joaquin basin were widespread and contributed to the compositional maturity of sandy sediments.

Thus, the Neogene wrench-tectonic regime set up numerous and various structural traps (e.g., Elk Hills anticline), combination structural-stratigraphic traps (e.g., San Ardo Field), and generally modestly buried, attractive reservoir sections (Fig. 3-5g). Key, however, to the remarkable petroleum potential of the Neogene strata of central California is the petroleum source-rock story. The deep-marine basins set up by triple-junction migration provided receptacles in which extraordinary thicknesses of Neogene sediment (Fig. 3-5i), largely assigned to the Monterey Formation (Fig. 3-3), accumulated. Much of this sediment is biogenous, reflecting upwelling systems along the eastern margin of the Pacific basin and biologic response to those oceanographic systems (Ingle, 1981a). Middle Miocene sections consist of calcereous mudstones rich in foraminifera and nannoplankton (Fig. 3-5d), whereas the Upper Miocene–Lower Pliocene is noted for its biosiliceous, diatomaceous character (Fig. 3-5e). The remarkable expansion of biosiliceous sedimentation over much of coastal California during the Late Miocene also reflects nontectonic factors such as high stands of sea level and global cooling (Graham and Williams, 1985). However, the thick biogenic Monterey sediments could not have accumulated and been preserved without transform-related catchment basins. Furthermore, cessation of arc volcanism and the borderland topography of the wrench system prevented the dilution of pelagic biogenic sediments by mainland-derived terrigenous sediments.

Kerogen in the Monterey Formation of central California is dominantly oil-prone. Type II kerogen derived from marine plankton (Fig. 3-5h). Type III kerogen occurs as well (Fig. 3-5h), however, in areas that had access to terrestrially derived sediment (Graham and Williams. 1985). A particularly interesting species of organic matter commonly associated with laminated intervals of the Monterey Formation is a filamentous, stromatolite-like structure tentatively identified as fossil bacteria (Williams, L. A., 1984). In addition to likely being significant contributors to the oil-prone kerogen assemblage of the Monterey Formation, these fossil bacteria signal special paleoenvironmental conditions. Analogous modern sulfur-oxidizing bacteria colonize the seafloor at the boundary between low-oxygen and normal-oxygen water masses (Williams, L. A., 1984). Thus, these bacteria signal the anaerobic/dysaerobic conditions necessary for optimum preservation of organic matter in sediments, a key prerequisite for significant petroleum generation (Demaison and Moore, 1980). Low-oxygen conditions, reflected in the widespread occurrence of low-oxygen biofacies and laminated sediments in the Monterey Formation, likely resulted from the impingement of an expanded oceanic low-oxygen water layer upon the central California coast, and were enhanced by the existence of silled borderland basins and heightened biologic productivity in the water column.

Kilometers of stratigraphic thickness of such sediments accumulated during the Miocene and Early Pliocene (Fig. 3-5i) in a happy conspiracy of wrench structuring, paleoceanography, and biologic response. Catagenesis of organic matter was promoted by this extreme burial, and perhaps, transiently higher heat flow associated with triple-junction extensional tectonism, but high Monterey sedimentation rates probably depressed isotherms and tended to offset the enhancing factors to some degree (Graham and Williams, 1985). Nevertheless, the Monterey was sufficiently deeply buried in the depocenters of most Neogene basins (Fig. 3-3) that most workers acknowledge it as the source for much of the oil and associated gas in central California. Which stratigraphic portions of the Monterey have served as principal petroleum sources varies from basin to basin, depending on subsidence and sediment accumulation history. For instance, the post-Miocene section in the Salinas basin is thin and largely nonmarine (Fig. 3-3, column 3), and apparently, only the deeply buried Middle Miocene lower portion of the Monterey is thermally mature and oil generative (Mertz *et al.*, 1983). On the other hand, thick accumulations of Plio-Pleistocene sediments promoted the maturation of kerogen in even the upper Monterey in much of the San Joaquin basin (Fig. 3-5i) and the Santa Maria basin (Fig. 3-3).

Although the extraordinary thickness of fine-grained Neogene source rocks in coastal California basins probably tended to reduce the efficiency of expulsion of generated petroleum. the billions of barrels of oil in Miocene and younger traps bear witness to the successful migration of significant quantities of oil. Apparently, interleaving of coarse clastics like the Stevens deep-sea-fan system and basinal source rocks provided efficient migration pathways. In addition, fracturing of diagenetically altered diatomaceous Monterey rocks (porcelanites and cherts) probably also promoted migration, and locally, even created fractured "shale" reservoirs.

SUMMARY

The distribution of oil and gas in central California is clearly controlled at a first order by tectonic setting.

The late Mesozoic and earliest Tertiary forearc system yielded attractive reservoir geometries, thick shale sections. and deep burial, but few structural traps. poor reservoirs, and gas-prone source rocks. The result is a modest gas-producing province in the Sacramento basin; the San Joaquin basin may have similar potential, with the exception of oil-prone source rocks at the top of the Great Valley section, but it remains largely untested due to the great depth of burial of the Cretaceous in most areas.

Paleogene facies reflect a continental borderland created by the tectonic emplacement of the Salinian block in the Late Paleocene. Arkosic sandstone compositions, lenticular reservoir geometries, and oil-prone source-rock facies permitted the generation and accumulation of oil in significant quantities in the San Joaquin, and locally in the Santa Cruz and Sacramento basins. Gas occurs in Eocene rocks of the Sacramento forearc basin. Where source-rock facies did not exist or Paleogene section is absent, Paleogene production is absent, as in the Santa Maria and Salinas basins. Contributing further to regional spottiness of Paleogene petroleum accumulations is the deep burial and concommitant reservoir degradation of Paleogene rocks in many areas.

Neogene strata accumulated in strike-slip successor basins developed atop the Salinian block and the Mesozoic forearc basin. Wrench tectonism produced numerous structural traps, as well as syntectonic combination structural-stratigraphic traps. Basin compartmentalization in the transform borderland permitted accumulation of great thicknesses of biogenic sediment derived from continental-margin upwelling systems. This key element of the highly petroliferous Neogene tectonostratigraphic regime depended on the serendipitous coincidence of nontectonic factors of paleoclimatology and paleoceanography with the tectonic development of sedimentary basins. Under widespread conditions of deep burial, Neogene source rocks generated most of the billions of barrels of oil (and associated gas) housed in the Neogene basins of central California. Only the northernmost basin, the Sacramento basin, persisted during the Neogene as a

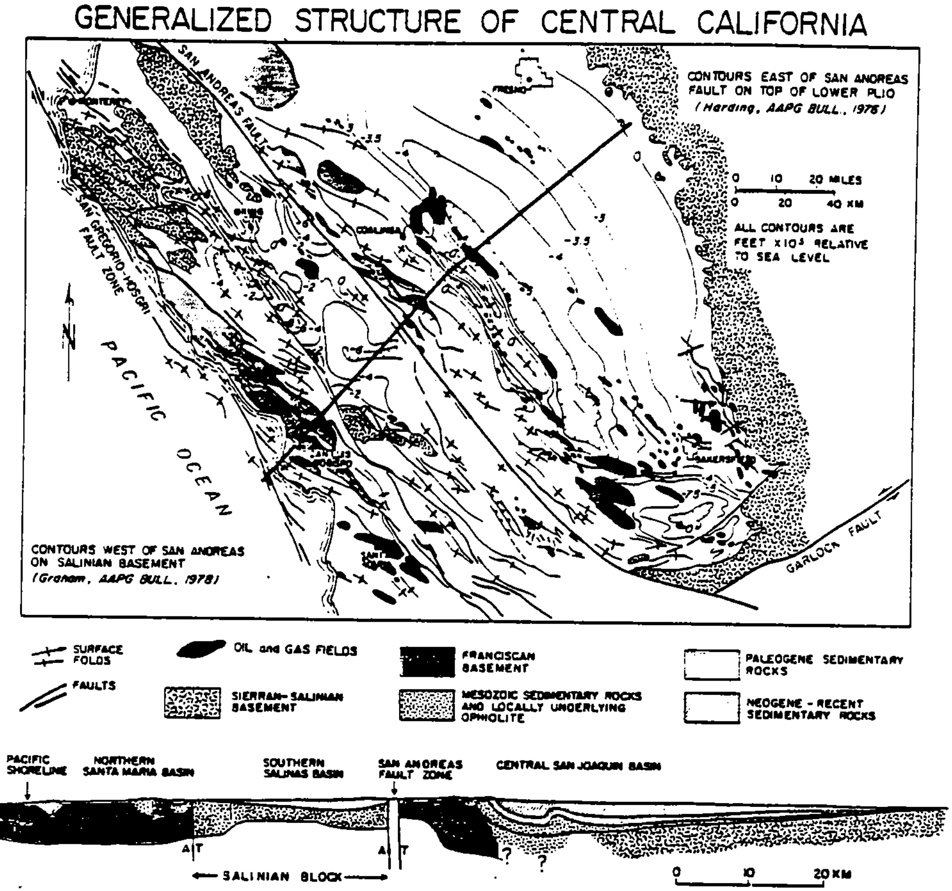


Fig. 3-6. Generalized structure of central California, emphasizing spatial distribution of Mesozoic basement types and major petroleum accumulations. Surface geology modified from Jennings *et al.* (1977); cross section from Page *et al.* (1979); oil and gas fields from Munger (1981).

nonmarine forearc basin outside the family of transform-margin basins, and it is virtually devoid of significant hydrocarbon accumulations.

From these relations, there is a tendency to conclude that the gas-prone Mesozoic Great Valley forearc system, like most forearc basins, is far less attractive for exploration than is the Neogene transform basin system. While undeniably true, there are factors of inheritance imparted from the Mesozoic system to the Neogene system, without which the Neogene system probably would have been far less petroliferous. The Mesozoic convergent-margin system and accreted Salinian block formed the foundation for Neogene successor basins, with some basins being underlain by crystalline arc basement and others being underlain by the Franciscan subduction complex (Fig. 3-6). During the Neogene, the relatively rigid Mesozoic arc basement remained relatively undeformed. Basement structure is simple, and mesoscopic structures in basement and cover rocks are largely limited to high-angle reverse and normal faults (Fig. 3-6). Consequently, associated petroleum traps are simple and relatively few in number. The Salinas basin has only one known major accumulation, and it is immediately adjacent to the only moderately thick accumulation of Neogene sediments in the basin (Figs. 3-1 and 3-6). Just as the rigidity of Salinian granitic basement limited deformation of cover rocks, so it also likely limited subsidence and thick sediment accumulations. Even the most oil-rich region underlain by arc basement, the Bakersfield area of the San Joaquin basin, is characterized by simple structures (Fig. 3-6) that, with few sealing beds, are mantled in some cases by residual tar sands rather than being true hydrocarbon traps.

The situation is much different in areas underlain by the Franciscan subduction complex. Already pervasively deformed by Mesozoic subduction, Franciscan basement was easily reshaped by Neogene wrench tectonism. In fact, the much-referenced study of wrench tectonics by Wilcox *et al.* (1973) used the western margin of the San Joaquin basin as an actualistic analog to their clay-cake models (note that they deleted the nearly undeformed granitic basement of the Salinian block immediately across the San Andreas fault in their Fig. 5). Because of the physical properties of the Franciscan basement, Neogene sections are generally thickest. Neogene folds have greatest amplitudes (3 km of transverse structural relief in the case of Kettleman North Dome: Page *et al.*, 1979), and structures are most complex where basins are underlain by the Mesozoic subduction complex (Fig. 3-6). Consequently, trapping opportunities for oil are most numerous, diverse, and volumetrically large in these areas as well. Contrast, for example, the field distribution in the arc-underlain Santa Cruz, Salinas, and eastern Great Valley basins with the field distribution in the Franciscan-floored Santa Maria and western Great Valley basins (Fig. 3-6).

Thus, the continental margin of central California holds a final important lesson for those who study sedimentary basins, as well as for those who search for petroleum. Current tectonic setting usually plays an obvious role in determining basin attributes, but closer study may reveal features inherited from previous tectonic regimes that subtly but effectively shape basin development.

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