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PALEOGENE TECTONICS AND SEDIMENTATION OF COASTAL CALIFORNIA

ABSTRACT

The paleogeography, paleotectonic framework, and depositional history of California's Paleogene basins are complex and influenced by many important factors. Tectonism of various types and styles characterized the Paleogene, a time of transition from a late Mesozoic Andean-type continental margin to a Neogene transform-type margin. Uplift of source areas, formation of basins, and subsidence of basins were controlled by: (1) active subduction that was oblique and at a relatively low angle; (2) detachment and dispersal of fragments of the late Mesozoic continental margin; (3) accretion of exotic terranes; (4) uplift of Mesozoic batholithic complexes; (5) development of local volcanic centers and migration of volcanic arcs; (6) regional uplift associated with the approach of the Pacific-Farallon spreading ridge and Mendocino fracture zone to southern California; and (7) initiation of a transform margin near the end of the Paleogene.

Paleogene source areas consisted mostly of uplands underlain by Mesozoic batholithic complexes in the Klamath Mountains, Sierra Nevada, Mojave Desert, Basin and Range, and Peninsular Ranges provinces. The Great Valley forearc basin evolved into two separate basins, the Sacramento and San Joaquin, divided by the Stockton arch. Accretion of the Salinian block during the early Paleogene resulted in the development of a continental borderland off central and southern California. Uplifted Mesozoic granitic and metamorphic basement rocks supplied sediment to numerous deep-sea fans deposited in the narrow, restricted basins of the borderland, and some of these fans spilled over into the San Joaquin basin. Subduction probably continued along the California continental margin throughout the Paleogene, as indicated by the presence of Paleogene and Neogene strata in the coastal belt of the Franciscan Complex in northern California; however, this subduction was probably complex and included a significant component of northward translation of coastal blocks. In the Oligocene, regional uplift and fracturing of the crust led to deposition of coarse, nonmarine deposits in numerous, narrow, fault-bounded basins; deep-marine sequences are restricted to only a few areas.

INTRODUCTION

From the Late Jurassic to the Oligocene, California was characterized chiefly by an Andean-type margin (Dickinson, 1979). An eastward-dipping subduction zone defined by a trench and subduction complex, an arc-trench gap defined by a large forearc basin, and a magmatic arc defined by a batholithic complex formed the main components of the California portion of the Pacific margin of North America (Figs. 5-1 and 5-2). For the Late Cretaceous, these three elements are expressed by: (1) the highly deformed oceanic and deep-marine strata of the Franciscan Complex, which has been interpreted by most workers as a subduction complex; (2) the gently deformed westward-thickening and westward-deepening clastic sedimentary strata of the Great Valley Group, interpreted as the fill of a forearc basin; and (3) granitic plutons of the Sierra Nevada, Mojave Desert, and Basin and

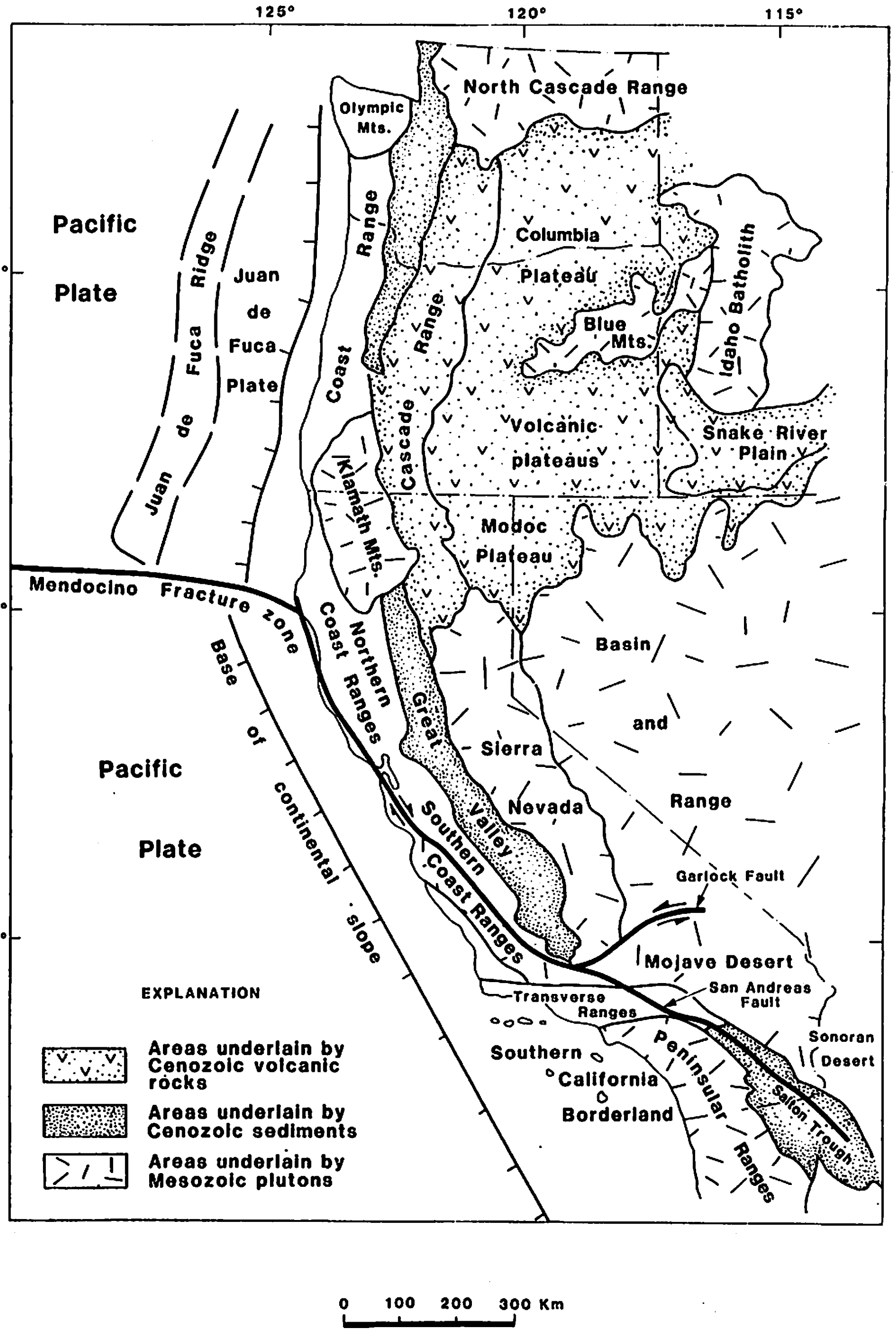

Fig. 5-1. Index map of the western conterminous United States showing major geologic provinces, areas underlain by Cenozoic volcanic rocks and sediments, and areas underlain by Mesozoic plutons.

nia Continental Borderland (herein referred to as the Southern California Borderland).

The purpose of this paper is to synthesize the geologic history and paleogeography of coastal California for the Paleogene interval. Many small basins developed during this interval as a result of the changing tectonic framework superposed upon the late Mesozoic Andean-type continental margin. The Paleogene basins were chiefly deep-marine in the Paleocene and Eocene, and nonmarine in the Oligocene. The change from marine to nonmarine conditions can be partly attributed to a climatic change to more arid and colder conditions that began in the Late Eocene (Peterson and Abbott, 1979), and to a major eustatic lowering of sea level by possibly as much as 350 m in mid-Oligocene time (Vail *et al.,* 1977a). However, tectonic activity remained the dominant force in controlling basin formation and filling in coastal California during the Paleogene (also, see Dickinson *et al.,* this volume, and Graham, this volume).

PREVIOUS WORK

The Paleogene paleogeography of California has been treated by many workers, only a few of whom have dealt with the entire state over the entire time interval. The first integrated reconstructions of the tectonic history and evolution of California basins by Reed (1933), and Reed and Hollister (1936) were beautifully conceived; in retrospect, however, they suffer from lack of modern understanding of large-scale strike-slip faulting, rotations of crustal blocks, marine microfossil correlations, and sedimentologic interpretations of turbidite facies. Reconstructions for the entire state can be found in Nilsen (1977c), a collection of papers that emphasize the late Mesozoic and Cenozoic history of California. Nilsen and McKee (1979) prepared a series of Paleogene paleogeographic maps for the entire western United States, including California.

Numerous other regional studies have been restricted to either smaller geographic areas within California or shorter time intervals. Nilsen and Clarke (1975) synthesized the Paleocene and Eocene paleogeography of California, concluding that it was dominated by a continental-borderland framework. Clarke *et al.* (1975) prepared four paleogeographic maps of California for specific early Tertiary intervals. Nilsen (1977b) summarized the early Tertiary paleogeography of California. Dibblee (1977) and Nilsen (1984a) prepared Oligocene paleogeographic syntheses for the entire state of California.

Other useful but even more areally or temporally restricted studies include: (1) a synthesis of Paleocene paleogeography of southern California by Sage (1973); (2) a synthesis of Middle Eocene paleogeography of southern California by Howell (1975b); (3) a synthesis of Oligocene paleogeography of southern California by Bohannon (1976); (4) paleogeographic studies of the northern Salinian block by Graham (1978); (5) regional analysis of the Paleogene strata of the Sacramento Valley region by Dickinson *et al.* (1979); and (6) reconstructions of the San Joaquin Valley by Bartow (this volume).

TECTONIC RECONSTRUCTIONS

Because many structural, paleomagnetic, paleontologic, and sedimentologic studies have demonstrated that some crustal blocks that make up the California margin have translated or rotated significant amounts, paleogeographic reconstructions for the Paleogene require major tectonic restorations of these movements. Five types of restorations are required to produce a suitable framework for paleogeographic maps: (1) restoration of movements on Neogene strike-slip faults of the San Andreas and related fault systems; (2) restoration of Neogene rotational movements of various tectonic blocks; (3) restoration of post-40-my B.P. extension, particularly in the Basin and Range, Mojave Desert, and Salton Trough provinces; (4) restoration of the large-scale northward translation of tectonostratigraphic terranes that appear to be exotic to the California margin; and (5) restoration of oceanic plates of the eastern paleo-Pacific Ocean to their positions relative to the North American plate during Paleogene time. Proper restoration of each of these paleotectonic elements is required to obtain accurate paleogeographic reconstructions for California.

The cumulative amount of displacement along northwest-trending strike-slip faults of the San Andreas fault system is probably about 1000 km (Fig. 5-3). The largest amount of slip has been along the San Andreas fault itself and is about 315 km (Dickinson *et al.,* 1972; Clarke and Nilsen, 1973). Other major amounts of slip along right-lateral faults (from north to south) include at least 75 km along the Grogan fault in the northwest Coast Ranges (Kelsey and Hagans, 1982), 43 km on the Hayward-Rodgers Creek fault (Fox *et al.,* 1985), 20 km on the Maacama fault (McLaughlin, 1981), 35 km on the Sunol-Calaveras-Franklin-Carneros fault (Page, 1982a; Fox, 1983), 115–150 km on the San Gregorio-Hosgri fault (Graham and Dickinson, 1978a; Clark *et al.,* 1984), 60 km on the Rinconada fault (Dibblee, 1976), 60 km on the San Gabriel fault (Crowell, 1982), 120–160 km on the East Santa Cruz Basin fault (Howell *et al.,* 1974), 30 km on the Elsinore fault (Crowell, 1981a), and 30 km on the San Jacinto fault (Sharp, 1967; Bartholomew, 1970; Crowell and Ramirez, 1979). In addition, there are smaller amounts of offset along numerous northwest-trending right-lateral faults within the Mojave Desert province (Garfunkel, 1974), and right-lateral offsets of as much as 80 km along the Death Valley fault zone and Walker Lane regions of the Basin and Range province (Stewart *et al.,* 1968; Bohannon, 1979).

Left-lateral Neogene displacements in the general region of the Transverse Ranges include 60 km on the Garlock fault (Smith, 1962; Dibblee, 1980a; Carter, 1982), 14 km on the Big Pine fault (Dibblee, 1976), 6 km or more on the Santa Ynez fault (Dibblee, 1978), and 60–90 km on the Malibu Coast–Santa Monica–Raymond Hill–Cucamonga fault (Sage, 1973; Campbell and Yerkes, 1976; Hall, 1981b). Thus, the cumulative amount of left slip in this area is about 150 km.

Significant rotations have affected parts of southern California in Neogene time (Luyendyk and Hornafius, this volume). The entire Transverse Ranges, including most of the Channel Islands, have rotated at least 75° in a clockwise manner, based on paleomagnetic studies of Miocene volcanic rocks and related units (Kamerling and Luyendyk, 1979). In addition, the southern Sierra Nevada

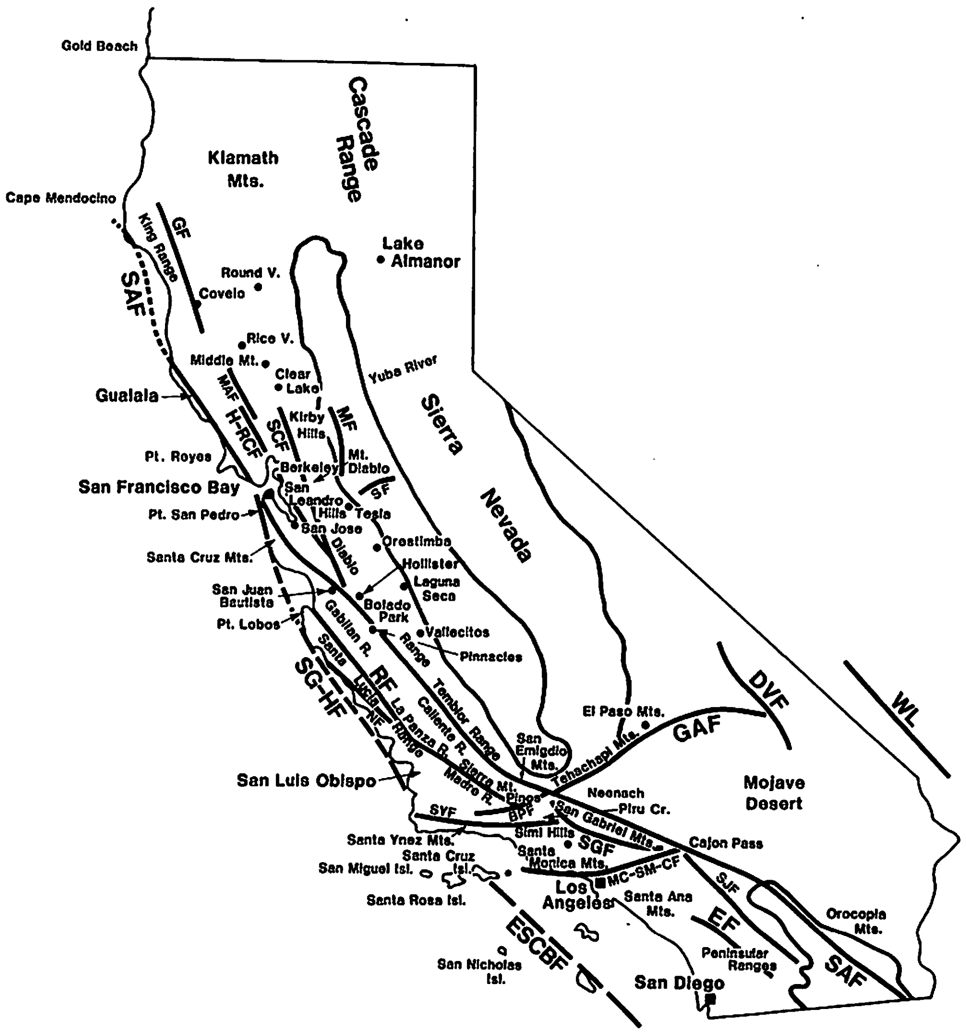

Fig 5-3. Index map of California showing location of important localities and faults mentioned in the text.

batholith and adjacent Tehachapi and San Emigdio Mountains have undergone 45 ± 14° of clockwise rotation between 80 and 20 my B.P. (Kanter and McWilliams, 1982); unpublished new paleomagnetic data from the area suggest an initial clockwise rotation of about 20° between 80-100 and 21-25 my B.P., and an additional 40° of clockwise rotation between 21-25 and 16 my B.P. (J. B. Plescia, written communication, 29 November 1985). Minor rotations, typically clockwise in nature, have affected many other parts of California, especially areas adjacent to major right-lateral faults and some large blocks such as the Peninsular Ranges, which appear to have rotated 32° clockwise (Hagstrum *et al.*, 1985).

During the last 40 my, extension in the Basin and Range, Modoc Plateau, and Salton Trough provinces has resulted in a net westward displacement of coastal California, including the batholithic complexes of the Klamath Mountains, Sierra Nevada, and Mojave Desert provinces (Stewart, 1983). Within the Basin and Range province, east-west extension has been estimated to total 60-100 km by Stewart (1971). Proffett (1977) estimated 30-100% extension in the central part of the province, and Wernicke *et al.* (1982) estimated 65-100% extension in the southern part.

Paleomagnetic, paleontologic, and stratigraphic data suggest that several large and many smaller exotic blocks or terranes have accreted to California in the Cenozoic (Coney *et al.*, 1980; Vedder *et al.*, 1983; Howell *et al.*, this volume). Many of these terranes, which include slivers of continental crust like the Salinian block, pieces of oceanic crust, fragments of volcanic arcs, and other types of crustal fragments, appear to have migrated northward from their places of origin prior to accretion. The Salinian block and the terranes west of it appear to have moved northward 2500 km since Cretaceous time (Champion *et al.*, 1984). Various fragments of oceanic crust and oceanic sedimentary rocks in the Franciscan Complex of the central and northern Coast Ranges have been shown to have been transported northward many thousands of kilometers (Alvarez *et al.*, 1980), some not accreting until post-Miocene time (McLaughlin *et al.*, 1982). Baja California and the Peninsular Ranges of southwestern California have been shown from paleomagnetic studies of batholithic rocks by Hagstrum *et al.* (1985) to have moved northward about 11°.

The processes of terrane formation, movement, and accretion complicate Paleogene paleogeographic reconstructions for coastal California in several ways. Terranes added to California in Neogene time have to be removed or restored to their original locations outside the state boundaries. Terranes presently located in other areas but suspected to have originally been located in California must be restored to their original locations; for example, various terranes in southwestern Oregon must be restored about 1200 km southward to a position opposite central California (Blake, 1984b).

Coastal California during the Paleogene was subjected to interactions among four major plates: the oceanic Kula, Pacific, and Farallon plates, and the continental North American plate. Major changes in the relative motions of these plates between 85 and 56 my B.P. caused significant changes in the tectonic framework of the eastern Pacific margin (Engebretson *et al.*, 1984b).

Most plate reconstructions of the western continental margin of North America for the Late Cretaceous and Paleogene show subduction of the Farallon plate beneath North America to the south, and northward movement of the Kula plate with regard to North America to the north (Atwater, 1970; Engebretson, 1982; Jurdy and Gordon, 1984). However, the location of the Kula-Farallon-North American triple junction during this interval is not well constrained by available plate reconstructions; as a result, the possibilities exist during the early Tertiary in coastal California for both right slip and convergence along the continental margin, depending upon which oceanic plates were present along the margin.

Most reconstructions for California indicate rapid convergence and subduction of the Farallon plate from 80 to 40 my B.P.; this convergence, possibly associated with subduction of an aseismic ridge, caused the Laramide orogeny and eastward migration of the active continental-margin magmatic arc (Dickinson and Snyder, 1978; Engebretson *et al.*, 1984b; Henderson *et al.*, 1984; Jurdy, 1984). Most of the continental plates, including North America, appear to have moved faster during the early Tertiary than at present (Jurdy and Gordon, 1984). However, a major northward component of relative movement in the Late Cretaceous to early Tertiary between North America and marginal oceanic plates is required to provide the suitable framework for northward movement of the Salinian block and other tectonostratigraphic terranes; this northward component of motion could have resulted from either Kula–North American plate motions or episodes of oblique Farallon–North American plate subduction (Page and Engebretson, 1984).

By mid-Oligocene time, the Pacific plate began to interact with the North American plate, initiating a new system of right-lateral shear that has culminated in the formation of the modern San Andreas fault system during the Neogene (Blake *et al.*, 1978). Thus, the late Paleogene saw development of two new triple junctions, one which migrated northward and one which migrated southward, resulting in the formation of new basins.

BATHOLITHIC SOURCE AREAS

Mesozoic magmatic arcs underlie much of California and formed the source areas for most of the sediments deposited in Paleogene basins. Plutonic rocks supplied huge amounts of arkosic sediments because most of the associated volcanic cover of the arcs had been stripped off by the beginning of the Tertiary (Ingersoll, 1983).

Batholiths of the Klamath Mountains are chiefly of Jurassic age (Irwin, 1981). Batholiths of northwestern Nevada and the northern Sierra Nevada are of Early Cretaceous and early Late Cretaceous (125–90 my) age (Smith *et al.*, 1971; Bateman, 1983), and those of the central and southern Sierra Nevada are of Triassic (about 206 my), Jurassic (186–155 my), and Early Cretaceous to early Late Cretaceous (125–88 my) age (Bateman, 1981). Granitic plutons of the Basin and Range province are of Late Triassic, Jurassic to Early Cretaceous (185–140 my), and Late Cretaceous (90–75 mg) age (Nelson, 1981). Abundant plutons in the Mojave Desert range in age from Early Triassic to early Tertiary (240–60 my) according to Burchfiel and Davis (1981), and those of southeastern California are of Triassic, Jurassic (180–160 my), and Late Cretaceous (90–75 my) age (Crowell, 1981a). One pluton in the Transverse Ranges has yielded a Late Cretaceous (80 ± 10 my) U-Pb age (Ehlig, 1981), and abundant Late Jurassic and Early Cretaceous (150–90 my) plutons form the main crustal component of the Peninsular Ranges (Gastil *et al.*, 1981).

The Salinian block is underlain by numerous plutons that have yielded emplacement ages of 117–106 my (Mattinson, 1978; Page, 1981). These plutonic rocks also have yielded abundant Late Cretaceous cooling ages from K-Ar and fission-track techniques (Ross, 1978).

CALIFORNIA PALEOGENE BIOSTRATIGRAPHIC ZONATION

Paleogene biostratigraphic zonations in California were originally based on molluscan fossils (Addicott, 1972c) and benthic foraminiferal assemblages (Schenck and Kleinpell, 1936; Kleinpell, 1938; Mallory, 1959). However, problems encountered in correlating California stages with European stages and with sequences penetrated by the Deep Sea Drilling Project in various ocean basins indicated that correlation of the California stages required additional biostratigraphic control from planktic foraminifers, radiolarians, diatoms, coccoliths, and other pelagic microfossils. The general lack of datable volcanic rocks in Paleocene and Eocene strata, as well as the abundance of poorly dated nonmarine rocks of Oligocene age, have also hindered the development of a well-defined biostratigraphic zonation in California.

The revised stage assignments for California shown on Fig. 5-4 are based on syntheses of new data by Poore (1976, 1980); additional detailed Paleogene microfossil correlations for California can be found in Brabb (1983). Many of these stages are not known as precisely as they are indicated on this figure, but for the purposes of preparing a regional paleogeographic synthesis, they will be used as shown. The range of each series in terms of absolute time is Paleocene: 66–58 my B.P.; Eocene: 58–37 my B.P.; and Oligocene: 37–24 my B.P., based on the new Decade of North American Geology time scale (Palmer, 1983). Global cycles of relative change of sea level for Paleogene time, based on the work of Vail *et al.* (1977a), are also shown on Fig. 5–4.

LATE MESOZOIC TECTONIC FRAMEWORK

The Late Cretaceous paleogeography of California was dominated by uplands underlain by the Mesozoic batholithic complexes, the large forearc basin in which the Great Valley Group and Hornbrook Formation were deposited, and a trench to the west along the continental margin, along which the Franciscan Complex accumulated by tectonic and sedimentary processes (Bailey *et al.*, 1964; Dickinson, 1976). Huge volumes of sediment were supplied to the forearc basin from source areas in the Klamath Mountains and Sierra Nevada (Ingersoll, 1979, 1983; Nilsen, 1984b); some of these sediments probably passed across the forearc basin to accumulate within trench-slope basins and within the trench, intermixing with Franciscan sediments derived from other sources (Ingersoll, 1979; Blake and Jones, 1981).

Upper Cretaceous deposits are not present beneath the southernmost San Joaquin basin or exposed in its surrounding mountain ranges (southern Sierra Nevada, Tehachapi Mountains, San Emigdio Mountains, and Temblor Range). They are also absent from the Basin and Range, Mojave Desert, Salton Trough,

Age	Series	Sub-series	California Stages		European Stages	
			megainvertebrate	foraminifers		
	Miocene	Lower	Saucesian	Saucesian		Burdigalian
						Aquitanian
24	Oligocene	Upper	Zemorrian	Zemorrian		Chattian
		Lower				Rupelian
37	Eocene	Upper	Refugian	Refugian		Priabonian
		Middle	"Tejon"	Narizian		Bartonian
			"Transition" "Domengine"	Ulatisian		Lutetian
		Lower	"Capay"	Penutian		Ypresian
58	Paleocene	Upper	"Meganos"	Bulitian	Selandian	Thanetian
						Unnamed
		Lower	"Martinez"	Ynezian		Danian
66	Upper Cretaceous	Maastri-chtian				Maastrichtian

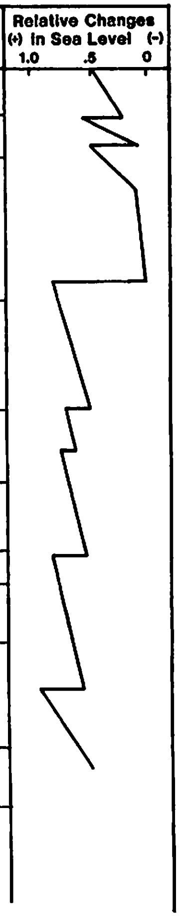

Fig. 5-4. Paleogene biostratigraphic zonation in California (modified from Poore, 1976, 1980; Palmer, 1983) and global cycles of relative change of sea level during the Cenozoic (modified from Fig. 3 of Vail *et al.*, 1977a). The horizontal units for rising and falling sea level indicate relative positions of sea level, with 1.0 being the maximum relative highstand and 0.0 the minimum relative lowstand.

and southeastern California. These regions were either uplands that were source areas during the Late Cretaceous or they were uplifted during early Paleogene time, with Cretaceous deposits being removed by erosion.

Upper Cretaceous strata are abundant in the Salinian block, Sur-Obispo terrane, Transverse Ranges, Peninsular Ranges, and parts of the Southern California Borderland (Nilsen, 1978). These areas, however, appear to have originally been located far to the south of their present latitude and did not form part of California during the Late Cretaceous (Vedder *et al.*, 1983; Champion *et al.*, 1984; Hagstrum *et al.*, 1985). The presence of turbidite sequences with westward-directed paleocurrents, magmatic-arc source areas, and structural juxtaposition with Franciscan-like rocks suggest that these areas are fragments of a convergent continental margin that included a magmatic arc, forearc basin, and subduction complex; these margin fragments may have originally developed as far as several thousand kilometers south of their present positions. These tectonic elements may originally have formed, with similar rocks in the Vizcaino area of central Baja California, a southward extension of the Franciscan–Great Valley–Sierra Nevada suite.

Upper Cretaceous rocks of the Gold Beach terrane of Blake (1984b) in southwestern Oregon appear to have been displaced northward from an original position at the latitude of California. Although these strata appear to have been deposited within a strike-slip regime (Bourgeois and Dott, 1985), they also resemble parts of the Great Valley Group and Franciscan Complex and could represent northward-displaced tectonic fragments of these units.

The inherited paleogeographic framework at the beginning of Paleogene time in California, thus, consisted principally of a remnant magmatic arc, a forearc basin, and a subduction complex. The arc was no longer active, the forearc basin had been substantially filled by deep-sea-fan, slope, and deltaic deposits, and the subduction complex had widened substantially as a result of tectonic accretion (Dickinson *et al.*, 1979; Ingersoll, 1979).

In the following summaries of Paleogene basins and their paleogeography and paleotectonic framework, basins are discussed in systematic order from north to south, first those located east of the San Andreas fault and second those west of the San Andreas fault. The summaries provide paleocurrent orientations in their present orientations, which are reoriented in subsequent reconstructions. Because of the huge number of references to Paleogene deposits, I generally limit citations to newer references published between 1975 and 1985. Where no references to particular basins or strata are found in the text, the reader is referred to the longer summary papers listed under "Previous Work" for applicable references, particularly to Clarke *et al.* (1975), Nilsen and Clarke (1975), Nilsen (1977c, 1984a), Dickinson *et al.* (1979), Nilsen and McKee (1979), and additional papers and references in this volume.

PALEOCENE BASINS

Although Paleocene strata are common in many parts of California, they have been removed by pre-Eocene erosion in some areas, making paleogeographic reconstructions of Paleocene basins difficult (Fig. 5-5). Three major aspects of the tectonic framework must be borne in mind for Paleocene reconstructions: (1) the southern extension or continuation of the Great Valley forearc basin was truncated in latest Cretaceous or Paleocene time, with detachment and dispersion of the remnants of the basin; (2) the Salinian block and Sur-Obispo terrane, as well as probably the western Transverse Ranges, Southern California Borderland, and Peninsular Ranges, were located south of their present locations, and do not appear to have accreted to California or northern Mexico until the end of the Paleocene or earliest Eocene; and (3) although the coastal belt of the Franciscan Complex contains rocks of Cretaceous to Miocene age, many of these rocks, including those of Paleocene age, are allochthonous and did not accrete to northern California until Eocene or later time. In terms of global sea-level changes,

Fig. 5-5. Map of California showing general location of Paleocene basins and outcrops of Paleocene rocks. The basins and outcrops are shown in their present locations.

major drops in sea level occurred at the Cretaceous–Paleocene boundary and near the end of the Paleocene at about 60 my B.P. (Fig. 5-4).

East of the San Andreas Fault

In northernmost California, Paleocene strata are generally missing, suggesting regional uplift. On the northern and eastern flanks of the Klamath Mountains, Eocene strata rest unconformably either directly on pre-Cretaceous basement rocks or on Upper Cretaceous deep-marine strata of the Hornbrook Formation (Heller and Ryberg, 1983; McKnight, 1984; Nilsen, 1984b). Paleocene strata are also missing from the southern flank of the Klamath Mountains and the western flank of the northern Sierra Nevada.

By the end of the Late Cretaceous and during the Paleocene, the Great Valley forearc basin became separated by the west-trending Stockton arch into two distinct basins, the Sacramento basin to the north and the San Joaquin basin to the south (Fig. 5-6). The Stockton arch may have been emergent, as suggested by the absence of Paleocene strata from the arch and the presence of shallow-marine and brackish-water deposits around its margin. The northeast-trending Stockton fault formed the northern flank of the Stockton arch and underwent as much as 600 m of vertical displacement.

The Paleocene Sacramento basin, in general, underwent continual southerly and westerly tilting, with periodic uplift along its western flank, particularly in the Mount Diablo area (Safonov, 1962). As a result of this tilting, the southwestern part of the basin is structurally the deepest, contains the thickest section of Paleogene strata, and consists mostly of deep-marine strata.

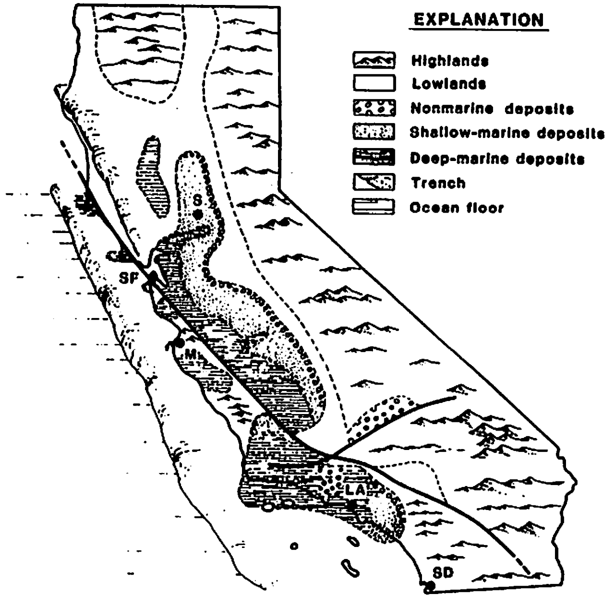

Fig. 5-6. Unrestored Paleocene paleogeographic map of California. The paleogeographic elements are shown in their present locations and orientations.

Lower Paleocene deposits of the southern Sacramento basin generally consist of deltaic facies to the east and shallow-marine facies to the west; major uplift and tilting of the basin in mid-Paleocene time truncated the Lower Paleocene and underlying Upper Cretaceous deposits, and resulted in the cutting of the Martinez Canyon, a major west-trending submarine canyon (Edmondson, 1962). This canyon was about 33 km long, as wide as 12 km, and as deep as 360 m (Almgren, 1984); it was filled with Upper Paleocene marginal-marine deposits to the east and deeper-marine deposits to the west (Pepper, 1984). A Late Paleocene transgression and rapid subsidence resulted in the deposition of as much as 900 m of turbidites and deep-marine shale in the southwestern part of the basin (Almgren, 1984).

West of the Sacramento basin, the coastal belt of the Franciscan Complex contains Paleocene turbidites that are tectonically intermixed with Upper Cretaceous and Eocene turbidites. The coastal belt is most reasonably interpreted to have accumulated in or adjacent to a tectonically active trench (Bachman, 1978, 1982) that was probably the continuation through time of the Mesozoic subduction zone in which older Franciscan rocks were deposited, accreted, and deformed. Although various trench-slope deposits, olistostromes, and deep-sea-fan sequences have been recognized in the coastal belt (Bachman, 1978), the Paleocene paleogeography cannot be differentiated from the Late Cretaceous or Eocene because of tectonic mixing of rock units.

Less-deformed Cretaceous and Paleocene strata rest depositionally on the Franciscan Complex in northern California in the Round Valley, Rice Valley, Middle Mountain, and Clear Lake areas (Berkland, 1972, 1973). These outliers have been interpreted to be trench-slope basins within the Franciscan subduction complex, but they could alternatively represent separate accreted terranes (Blake and Jones, 1981, p. 327) or fragments of the Sacramento basin that have been preserved in downfaulted blocks or along strike-slip faults (Dickinson *et al.*, 1979; McLaughlin and Ohlin, 1984).

West of the Stockton arch in the Coast Ranges, Paleocene strata of the Martinez Formation are as thick as 300 m on the north flank of Mount Diablo; they rest unconformably on the Great Valley Group, the lower part of the formation consisting of shallow-marine conglomerate and the upper of mudstone. Deep-marine turbidite and mudstone deposits of Paleocene age are also present in scattered outcrops in the San Leandro and Berkeley Hills, eastern Santa Cruz Mountains, and western Diablo Range in the vicinity of San Jose (Nilsen and Clarke, 1975).

In the San Joaquin basin and adjacent southern Coast Ranges, Paleocene strata are thick, abundant, and generally of marine origin. Paleocene strata generally thin and shoal northward onto the Stockton arch. On the northwest margin of the basin, outcrops of the Tesla Formation in the Tesla and Orestimba areas consist of several hundred meters of brackish-water deposits of sandstone and shale. In the Laguna Seca area, 370 m of shallow-marine sandstone, siltstone, and shale of the Laguna Seca Formation of Payne (1951) crop out.

In the Vallecitos area, Paleocene strata consist of the upper part of the Moreno Shale and the apparently unconformably overlying lower part of the Lodo Formation (Nilsen, 1981). The Moreno Shale is of deep-marine origin and forms the uppermost part of the Great Valley Group, which in this area extends across the Mesozoic-Cenozoic boundary. The Lodo Formation is a thick sequence of deep-marine clastic strata divisible into four members, the lower three of which are of Paleocene age (Nilsen, 1981). The laterally discontinuous basal unnamed sandstone member, as thick as 230 m, is overlain by the Cerros Shale Member, as thick as 305 m. The thick Cantua Sandstone Member, the lower part of which is of Paleocene age, is as thick as 1375 m and forms a large lens-shaped deep-sea-fan complex within the Lodo Formation; paleocurrents indicate sediment transport dominantly toward the north, northwest, and northeast (Nilsen, 1981). The Cantua appears to have been fed by a large submarine channel or canyon present in the subsurface to the east that funneled sediment from its Sierra Nevada source across the Sacramento basin to the Vallecitos area (Graham and Berry, 1979). In the Coast Ranges west of the Vallecitos area, Paleocene basin-plain strata of the Bolado Park Formation of Sullivan (1965) crop out in the Bolado Park area; this unit consists of about 120 m of bathyal foraminiferal shale and mudstone with thin turbidite interbeds (Nilsen, 1981).

Farther south, along the western margin of the San Joaquin Valley, the Lodo Formation crops out locally as a discontinuous shale, the lower part deposited at bathyal depths and the upper part deposited at neritic depths (Mallory, 1970; Dibblee, 1973b). Along the southern and eastern margins of the San Joaquin basin, Paleocene strata are absent.

Paleocene subsurface units in the northern San Joaquin Valley consist of the brackish-water Tesla Formation along the northern margin and the laterally equivalent shallow-marine Laguna Seca Formation of Payne (1951) to the south (Bartow, 1985a). These units generally appear to unconformably overlie the Great Valley Group and record westward progradation of shelf deposits derived from the Sierra Nevada over underlying slope deposits of the uppermost Great Valley Group (Dickinson *et al.*, 1979). The Paleocene deposits are absent to the north on the Stockton arch as a result of post-Eocene erosion, and are truncated to the east by an angular unconformity at the base of overlying Eocene strata (Bartow, 1985a). In the central and southern San Joaquin basin, deep-marine shale of the Lodo Formation and the submarine-canyon deposits of the Cantua Sandstone Member characterize the Paleocene in the subsurface (Graham and Berry, 1979).

Along the southern margin of the Sierra Nevada, and Basin and Range provinces, poorly dated lower Tertiary nonmarine strata rest on granitic and metamorphic basement rocks and are unconformably overlain by Neogene volcanic and sedimentary rocks (Dibblee, 1967). In the southern Tehachapi Mountains, the Witnet Formation, as thick as 1200 m, consists of conglomerate overlain by sandstone that was deposited by fluvial processes in a northeast-trending lowland. Farther east, in the El Paso Mountains, the nonmarine Goler Formation, as thick as 2000 m, consists of a lower conglomerate and breccia unit derived from source rocks in the El Paso Mountains, and an upper sandstone and mudstone with local lenses of conglomerate derived from more-distant basement rocks. The Goler Formation was also deposited in a northeast-trending lowland by fluvial processes.

In the Mojave Desert province, marine strata thought to have been of Paleocene age and assigned to the San Francisquito Formation rest unconformably on granitic and metamorphic basement rocks adjacent to Cajon Pass (Dibblee, 1973b). However, plesiosaur remains recently found in these deposits support a Cretaceous age and indicate that these rocks are not related to the type San Francisquito Formation (Kooser, 1982).

West of the San Andreas Fault

Paleocene strata form abundant but scattered outcrops in the Salinian block. In the Gualala area, conglomeratic and sandstone-rich deep-sea-fan deposits of the German Rancho Formation of Wentworth (1968) are at least 3000 m thick and rest conformably on underlying Cretaceous deep-sea-fan deposits. The lower part of the German Rancho Formation is of Paleocene age. Paleocurrents indicate sediment transport toward the northwest (Wentworth, 1968).

At Point Reyes, the Paleocene Point Reyes Conglomerate is as thick as 210 m and rests unconformably on granodioritic basement rocks (Galloway, 1977). The Point Reyes Conglomerate was interpreted by Clark *et al.* (1984) to have been deposited as a northwest-flowing middle-fan channel complex, but because it has been eroded into basement rocks, it is more likely an erosive remnant of a submarine canyon.

At Point San Pedro, Paleocene turbidites that are at least 1000 m thick rest unconformably on granitic basement rocks (Morgan, 1981; Nilsen and Yount, 1981). The sequence consists of basal submarine-canyon and slope deposits overlain by inner-fan and middle-fan deposits, transported toward the northwest.

In the La Honda basin, Paleocene strata of the Locatelli Formation rest unconformably on granitic basement rocks on the southern flank of the basin (Clark, 1968, 1981). The Locatelli Formation is as thick as 300 m and consists of basal shallow-marine conglomerate and sandstone overlain by deep-marine siltstone with thin-bedded turbidities.

At Point Lobos, the Carmelo Formation of Bowen (1965) rests unconformably on granodioritic basement rocks (Addicott, 1978). It is 220 m thick, consists of a lower unit of conglomerate and an upper unit of interbedded turbidite sandstone and shale, interpreted to have been deposited by various processes in a west-trending submarine-canyon complex (Clifton, 1981b, 1984).

In the northern Santa Lucia Range, erosional remnants of Paleocene strata of the Merle Formation of Compton (1957) are as thick as 1525 m; these strata conformably overlie Upper Cretaceous deposits and locally rest directly on granitic basement (Graham, 1979b). The Merle Formation consists of bathyal inner- and middle-fan deposits transported by southwest-flowing turbidity currents (Reutz, 1979). It is unconformably overlain by shallow-marine Eocene strata of the Reliz Canyon Formation, which contains a basal Upper Paleocene reeflike limestone and locally rests directly on granitic and metamorphic basement (Graham, 1979b). Farther south, Paleocene strata as thick as 400 m were deposited in both shallow-marine and deep-marine environments (Durham, 1974).

In the La Panza, southern Santa Lucia, and Sierra Madre Ranges, a thick section of Upper Cretaceous to Lower Eocene strata crops out over a wide area and rests unconformably on granitic basement. The Paleocene strata reflect northward and eastward shoaling, and sediment transport dominantly toward the south and west within the Sierra Madre basin (Chipping, 1972; Sage, 1973).

In the Caliente Range, Paleocene turbidites of the Pattiway Formation are as thick as 1100 m (Sage, 1973). These units were derived from granitic and metamorphic basement rocks and deposited as submarine fans by turbidity currents that flowed toward the southwest, south, and southeast.

In the Santa Ynez basin, Paleocene strata of the lower Anita Shale crop out in the western Santa Ynez Mountains. It consists of shale as thick as 300 m with thin-bedded turbidites, deposited in a basin that deepened southward, fed by turbidity currents that flowed toward the south and southwest (Gibson, 1972, 1973). Scattered lenses of algal limestone are present in the lower part of the Anita Shale. In the northern, central, and eastern Santa Ynez basin, Paleocene strata appear to be absent, although the lower parts of the thick Eocene sequence may include Paleocene strata. In the Piru Creek area at the eastern margin of the basin, 5200 m of Paleocene and Eocene strata rest unconformably on granitic basement rocks; the Paleocene part of the section, about 700 m thick, was deposited as a submarine fan by southwest-flowing turbidity currents (Sage, 1973). To the south, in the Channel Islands, Paleocene strata of the lower parts of the Pozo and Cañada Formation consist of shallow-marine and deep-marine deposits (Sage, 1973).

In the Simi Hills area, lower nonmarine and overlying shallow-marine strata as thick as 1150 m were transported southwestward from source areas underlain by granitic strata to the northeast (Sage, 1973). Similar strata in the Santa Monica Mountains crop out in four separate fault blocks and consist of alluvial-fan, shallow-marine, and deep-marine deposits as thick as 2600 m (Sage, 1973). Sediments were transported southwestward into a deepening basin from granitic and metamorphic source rocks to the north and east.

In the San Gabriel Mountains, the San Francisquito Formation consists of a basal 100 m of shallow-marine clastic and carbonate rocks that rest unconformably on granitic and metamorphic basement and are overlain by almost 4000 m of deep-sea-fan deposits (Kooser, 1982). Paleocurrents generally indicate progradation of the fan toward the south and west.

In the Santa Ana Mountains, Paleocene strata of the Silverado Formation, as thick as 570 m, rest unconformably on Upper Cretaceous sedimentary rocks and granitic basement (Yerkes *et al.*, 1965). The unit consists of a basal nonmarine braided-stream conglomerate overlain by fluvial and lagoonal deposits; the upper part of the section consists of fossiliferous shallow-marine sandstone. Sage (1973) determined sediment transport toward the south-southwest and inferred a granitic source area to the northeast.

In the northern San Diego area, estuarine deposits previously considered to be of Cretaceous age, in the lower part of the Mount Soledad Formation, are now thought to be of Late Paleocene age (Kies, 1982a,b; Walsh and Estes, 1985). These deposits define a northwest-trending shoreline on the western margin of the Peninsular Ranges.

Paleocene Paleogeography and Paleotectonics

Paleocene strata were deposited in numerous separate basins that evolved from the Late Cretaceous convergent margin (Fig. 5-5). Paleocene rocks of the coastal belt of the Franciscan Complex record the continued presence of a subduction complex in northern California. The Sacramento and San Joaquin basins had become separate as a result of continued uplift of the Stockton arch. The Round Valley–Clear Lake basin may have formed a continuous trench-slope basin or several smaller trench-slope basins; the strata in the basin could also represent erosional remnants of the Paleogene fill of the Sacramento basin deposited east of the Paleogene trench-slope break (Dickinson *et al.*, 1979). The presence of angular unconformities, Franciscan detritus in the Paleogene sections, and faulting suggest that the western margin of the Sacramento basin underwent tectonic deformation and uplift by the Early Paleocene. Shallow-marine deposits of Maastrichtian age in the outlier of the Great Valley Group near Covelo indicate uplift in the Late Cretaceous (Gucwa, 1975).

Both the Sacramento and San Joaquin basins were fed primarily by sediment derived from the Sierra Nevada, with at least one major submarine canyon feeding deep-sea-fan deposits in each basin (Fig. 5-6). Both the Sacramento and San Joaquin basins generally deepened toward the south and west; the Stockton and

Midland faults exerted major control on sedimentation in the southwestern parts of the Sacramento basin.

The nonmarine Goler and Witnet basins in the area north of the modern Garlock fault formed a northeast-trending trough. This trough suggests the possible presence of a proto-Garlock fault that controlled basin formation and sedimentation (Nilsen and Clarke, 1975).

On the basis of paleomagnetic data, Paleocene rocks located west of the San Andreas fault appear to be allochthonous to California, having accreted in post-Late Paleocene time (Figs. 5-6 and 5-7). These allochthonous terranes include the Salinian block, Sur-Obispo terrane, Tujunga terrane, Transverse Ranges block, and Peninsular Ranges block. In addition to these allochthonous terranes, it is clear that the southern continuation of the Great Valley Group and its associated subduction complex have been detached, and probably transported northward by various processes of terrane dispersion; the present location of this block is uncertain.

These allochthonous and detached terranes are shown schematically in Fig. 5-7, not in their true positions, but in their relative positions west of the California margin. The California margin most likely was characterized by a trench, but subduction was oblique, at a low angle, and associated with major strike-slip displacements. The Salinian block and Sur-Obispo terrane were attached, and the Tujunga terrane may also have been attached to these two terranes, forming a larger composite terrane (Howell *et al.,* this volume); the small, restricted, and generally deep-marine Paleocene basins of the Salinian block were probably formed by crustal stretching that resulted from extension related to strike-slip faulting. Paleocene strata are absent from the Sur-Obispo and Tujunga terranes, which may have been uplifted areas within the composite terrane. Similarly, the Peninsular Ranges and Transverse Ranges block may have been attached as a composite terrane that originated farther north than the Salinian composite terrane. Paleocene deposits of the Transverse Ranges block may have formed a major north-south-trending basin surrounded by highlands (Fig. 5-7).

The Paleocene tectonic framework, thus, consisted dominantly of the same elements that had characterized the Late Cretaceous forearc-basin setting (Fig. 5-8). The subduction complex to the west had been uplifted, the forearc basin had been divided in half by uplift of the Stockton arch, and the southern extension of the forearc basin had been truncated and detached by faulting. From the south, allochthonous terranes were approaching California, to accrete in earliest Eocene time.

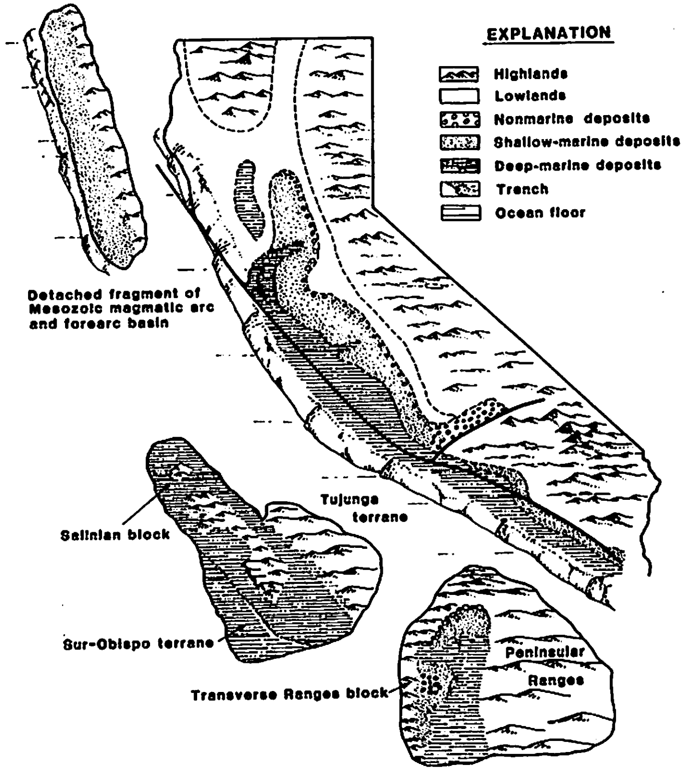

Fig. 5-7. Restored Paleocene paleogeographic map of California. The paleogeographic elements are shown in their Paleocene locations and orientations.

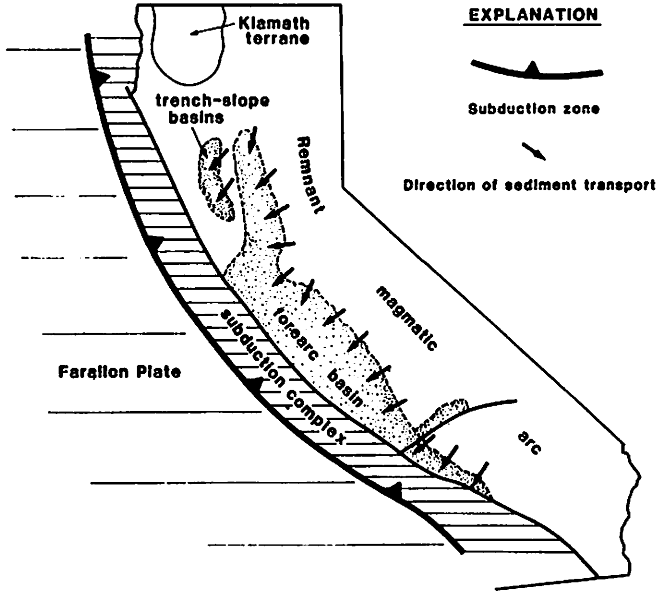

Fig. 5-8. Paleocene paleotectonic map of California. The generalized paleotectonic elements are shown in their Paleocene locations and orientations.

EOCENE BASINS

Eocene basins are widespread and of varying size and shape (Fig. 5-9). They record continuing tectonic activity, including the accretion of the Salinian composite

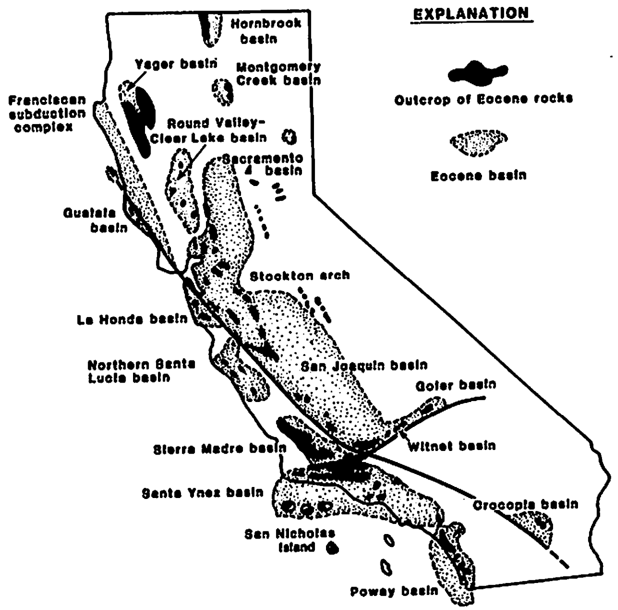

Fig. 5-9. Map of California showing general location of Eocene basins and outcrops of Eocene rocks. The basins and outcrops are shown in their present locations.

terrane and the Peninsular Ranges and Transverse Ranges blocks (Figs. 5-7 to 5-9). Marine sedimentation, particularly deep-sea-fan sedimentation, was dominant in Eocene California (Fig. 5-10). To the east and north, nonmarine strata are abundant, having been derived from erosion of the Mesozoic batholithic complexes, and locally, from Eocene volcanic-arc rocks. Eocene strata are particularly abundant and thick in the Coast Ranges, San Joaquin Valley, and Transverse Ranges.

Eocene climates were generally warm and humid, particularly in the Early and Middle Eocene, when lateritic weathering was locally common, anauxitic clays developed, and quartz-rich sandstones were deposited. In the Late Eocene, the climate began to change to colder and more arid conditions (Peterson and Abbott, 1977, 1979, 1981). Global curves of relative change in sea level indicate generally rising levels in the Early Eocene, a major lowering near the end of the Early Eocene, generally rising levels in the Middle Eocene, and several fluctuations at the end of the Middle Eocene and within the Late Eocene (Fig. 5-4).

East of the San Andreas Fault

In northernmost central California and extending into Oregon, Upper Eocene braided-stream deposits as thick as 2300 m of the Payne Cliffs Formation were shed northeastward into the Hornbrook basin (McKnight, 1984; Nilsen, 1984b). The Payne Cliffs Formation was derived from erosion of granitic and metamorphic rocks of the Klamath Mountains; it rests unconformably on Upper Cretaceous deep-marine turbidites of the Hornbrook Formation and is overlain by volcanic rocks of the Western Cascades Group (Vance, 1984). The formation generally fines upward, contains some coal, and includes tuff beds and volcanic detritus near its top, signaling the initial development of the Western Cascade volcanic arc to the east and north.

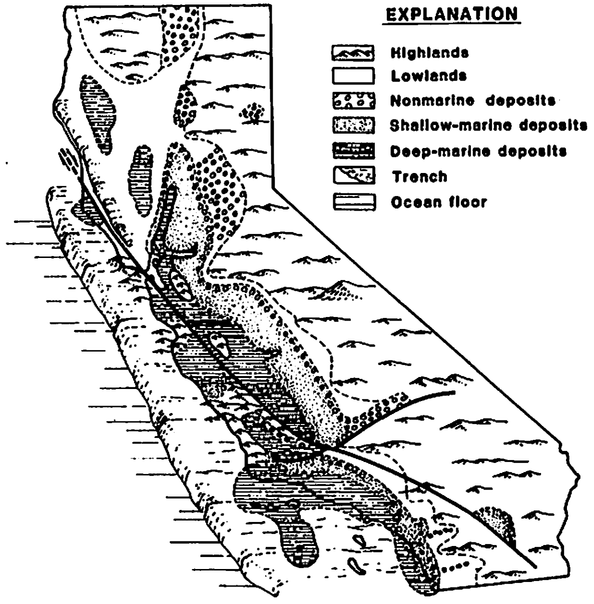

Fig. 5-10. Unrestored Eocene paleogeographic map of California. The paleogeographic elements are shown in their present locations and orientations.

Farther south, conglomeratic fluvial deposits of the Montgomery Creek Formation crop out on the east flank of the Klamath Mountains (Sanborn, 1960). These strata are as thick as 750 m and are of probable Late Eocene age; abundant andesitic volcanic clasts and south-southeast-directed paleocurrents suggest a volcanic-arc source to the north (Dickinson *et al.*, 1979).

At the northeast margin of the Sierra Nevada, east of Lake Almanor, Eocene fluvial conglomerates that were transported south-southwesterly toward the Sacramento basin rest unconformably on granitic and metamorphic basement rocks (Dickinson *et al.*, 1979). These conglomerates contain a mixture of granitic and volcanic clasts in their lower parts and quartz-rich resistant clasts in their upper parts.

South and southwest of the Klamath Mountains, Eocene strata form three separate outcrop belts within the Franciscan Complex. To the west, Eocene rocks accumulated and were deformed as part of the coastal belt of the Franciscan Complex (Bachman, 1978, 1982). Overlying these more highly deformed rocks, the coeval Yager Formation was deposited in trench-slope, slope-channel, and slope-basin settings (Underwood, 1983); it consists mostly of channel and interchannel turbidites that appear to have been deposited by southwest-flowing currents over a syndepositionally deforming subduction complex. Farther to the south, but still within the Franciscan Complex, outliers of Paleogene strata of the Round Valley–Clear Lake basin crop out; although dominantly of Paleocene age, Eocene strata that are generally finer-grained and glauconitic are present at Round Valley and Rice Valley (Berkland, 1973); these deposits could either have accumulated in trench-slope basins or be erosional remnants of the Eocene fill of the Sacramento basin.

Eocene nonmarine deposits are common within and along the western margin of the Sierra Nevada. East of the Sacramento basin, Eocene auriferous gravels were deposited by west-flowing streams. The gravels are generally less than 15 m thick, except along the ancestral Yuba River, where they are as thick as 180 m (Yeend, 1974). These fluvial gravels consist of lower "blue gravels," which contain various clasts from adjacent rock units and interbedded arkosic sandstone, and overlying "white gravels," which contain only resistant quartzose clasts and interbedded quartzitic and anauxitic sandstone, suggestive of deep chemical weathering in a tropical environment.

Farther south, the Ione Formation, as thick as 300 m, crops out along the west flank of the Sierra Nevada (Creely, 1965; Gillam, 1974). It consists of Lower Eocene deltaic, lagoonal, and fluviatile deposits, and has been divided into two members separated by an unconformity. The lower member rests directly on a deeply weathered lateritic surface and includes quartzose sandstone, anauxitic claystone composed mostly of kaolinite and halloysite, and lignite. The upper member consists of feldspathic sandstone and conglomerate. The contrast between the two members is indicative of major climatic change.

In the Sacramento basin, Eocene strata are widespread, thick, stratigraphically complex, and consist of many different facies. Although many stratigraphic subdivisions have been proposed for Eocene strata, both in subsurface and outcrop, Lower Eocene strata can regionally most simply be referred to the Capay Formation, and Middle Eocene strata to the Domengine, Nortonville, and Markley Formations (Cherven, 1983a).

Eocene paleogeography was influenced chiefly by the presence of two large submarine canyons cut at the end of the Paleocene during a lowering of sea level, and filled in the Early Eocene during a rise of sea level (Almgren, 1978). The Princeton canyon trended north-south and was cut along the present western margin of the Sacramento Valley; its maximum length was 265 km, its maximum width 40 km, and its relief on the order of 850 m (Redwine, 1984). The lower part of the canyon is filled with marine shale, turbidite sandstone, local conglomerate, and submarine landslide deposits of the Capay Formation, exposed along the west flank of the Sacramento basin (Baker, 1975); to the north, these deposits grade laterally into estuarine deposits. Abundant gas fields are present both within and on the margins of Princeton canyon (Frick *et al.*, 1984; Hacker, 1984).

The Meganos canyon has a more westerly trend in the southern Sacramento basin (Edmondson, 1984; Fischer, 1984). This canyon was 71 km long, as wide as 13 km, and had a relief as great as 762 m; the canyon fill crops out along the north side of Mount Diablo. The canyon was filled mostly with shale and minor amounts of turbidite sandstone that to the west grade into deep-sea-fan deposits (Fischer, 1979, 1984). Numerous gas fields and one oil field are present within and on the margins of Meganos canyon (Boyd, 1984).

The Capay Formation and correlative units form a thin (60- to 90-m-thick) blanket of glauconitic siltstone and claystone that unconformably overlies Paleocene and older strata throughout most of the Sacramento basin. The units were deposited at moderate depths, under stagnant bottom conditions, and record basin-wide transgression; conglomerate and sandstone to the north and east suggest source areas in those directions. The Capay Formation thickens to the northwest and west of the Midland fault, defining a northwesterly and westerly paleoslope (Cherven, 1983a).

The Domengine Formation is a widespread shelf sandstone about 150 m thick that records westward progradation of a tide- and wave-dominated deltaic system (Bodden, 1983; Cherven, 1983b). To the east and north, it grades laterally into coal-rich fluvial deposits of the Ione Formation. Uplifts to the south and west in the Mt. Diablo, Kirby Hills, and Stockton arch areas resulted in an irregular restricted basin surrounded by source areas.

Subsidence of the Sacramento basin in the late Middle Eocene yielded inundation of the Stockton arch and Mount Diablo areas and widespread deposition of the Nortonville Formation (Cherven and Bodden, 1983). Lower-bathyal shale west of the Midland fault and shallow-marine sandstone east of the fault record a west-sloping basin.

The Markley Formation is as thick as 1400 m and consists mostly of sandstone. It records westerly transport of sands derived from a Sierran source. Water depths increased to the west; to the south, the Markley Formation is missing on the south flank of Mount Diablo. Post-Eocene erosion truncates the Markley Formation to the north and east. In Late Eocene time, a regression resulted in the cutting of Markley canyon (Almgren, 1984).

In the San Francisco Bay region, Eocene strata form widespread but scattered outcrops. In the northwestern Diablo Range, strata equivalent to and similar to the Capay and Domengine Formations are about 300 m thick. In the San Jose area, Eocene strata rest unconformably on Franciscan basement and consist of shallow-marine breccia overlain by deep-sea-fan deposits that have mostly Sierran source areas and form scattered outcrop areas. These turbidites may have been deposited as deep-sea fans fed by the large submarine canyons of the Sacramento basin (Nilsen and Clarke, 1975).

Eocene strata of the San Joaquin basin are also stratigraphically complex, and include strata derived from Sierran, Mojave Desert, Franciscan, and Salinian sources. The basin generally shoaled northward onto the Stockton arch, eastward onto the flank of the Sierra Nevada, and northwestward onto uplifted parts of the Diablo Range (Nilsen and Clarke, 1975). From east to west, fluvial, marine-shelf, slope, basin-plain, and deep-sea-fan deposits can be differentiated.

In the northern part of the basin, shallow-marine to brackish-water deposits of the Lower Eocene Tesla Formation include glauconitic sandstone, carbonaceous siltstone, and anauxitic quartzose sandstone as thick as several hundred meters. This formation was derived from the Sierra Nevada and is overlain unconformably by thin Middle Eocene shallow-marine deposits of the Domengine Sandstone, which in turn, is overlain by the Kreyenhagen Shale. The Kreyenhagen is 210 m thick and includes diatomaceous and radiolarian shale, limestone lentils, volcanic ash layers, and glauconitic sandstone; the upper part of the Kreyenhagen Formation records sedimentation in deeper-marine environments. The Kreyenhagen Formation grades northward into, and is overlain by, quartz-anauxitic-kaolinitic sandstone of the Middle Eocene Poverty Flat Formation (Bartow, 1985a). On the northeastern side of the San Joaquin basin, the nonmarine to paralic Ione Formation is correlative with marine units to the west and south. The entire Eocene sequence is unconformably overlain by Upper Oligocene and Miocene nonmarine strata.

To the south in the San Joaquin basin, Lower Eocene strata of the Tesla Formation grade laterally into the upper part of the Laguna Seca Formation, deposited under shallow-marine conditions (Bartow, 1985a). These shelf deposits grade laterally southward into deeper-marine shale of the Lodo Formation, which in the Vallecitos area, contains the Cantua Sandstone Member, a large deep-sea-fan deposit derived from the Sierra Nevada (Graham and Berry, 1979; Nilsen, 1981). On the west side of the Diablo Range, a smaller deep-sea-fan deposit of Early Eocene age crops out southeast of Hollister; this unit, the Tres Pinos Sandstone, is 270 m thick and appears to have been derived from the Salinian block (Nilsen, 1981). South of the Vallecitos area, Lower Eocene deposits are represented by the laterally discontinuous Lodo Formation, chiefly deep-marine shale that is as thick as 90 m (Dibblee, 1973b).

Lower Eocene strata of the northern and western San Joaquin basin are overlain with local unconformity by various shallow-marine sandstone units that record widespread uplift and shoaling of the basin. The shallow-marine units include the Domengine Sandstone, Yokut Sandstone, and Avenal Sandstone, which rest unconformably on Cretaceous strata; these units are as thick as 200 m and record deposition in shallow-marine, deltaic, tidal-channel, sand-flat, and locally fluvial environments (Slagle, 1979; Kappeler *et al.*, 1984). In the Vallecitos area and Temblor Range, abundant Franciscan detritus in these units indicates uplift of the central and southern Coast Ranges; a major angular unconformity in the Vallecitos area documents strong folding of older strata (Nilsen, 1981).

These shallow-marine units are overlain conformably by deep-marine shale of the Kreyenhagen Formation, which blanketed most of the San Joaquin basin in the late Middle Eocene and Late Eocene (see references in Blueford, 1984). However, in the Temblor Range, a large deep-sea fan, derived from the Salinian block to the west, prograded basinward to pinch out into the Kreyenhagen Formation. This unit, the Point of Rocks Sandstone, is as thick as 880 m, was deposited in bathyal or greater depths, and has northeastward-directed paleocurrents.

In the subsurface of the southern San Joaquin basin, the deep-marine Kreyenhagen Formation grades eastward into shallow-marine deposits of the Famosa sand, which are 60–180 m thick. The Famosa grades laterally eastward into nonmarine deposits of the lower Walker Formation (Bartow and McDougall, 1984).

At the south end of the San Joaquin Valley, Eocene strata exposed in the San Emigdio and western Tehachapi Mountains record a similar west-to-east gradation from deep-marine shale and interbedded turbidites to shelf deposits to alluvial deposits (Nilsen, 1984c). The Tejon Formation, as thick as 1200 m, has a basal marine conglomerate that records an Early to Middle Eocene west-to-east transgression over crystalline basement rocks, followed by a late Middle Eocene regression, in which shallow-marine sandstone and lagoonal siltstone are overlain by westward-prograding fanglomerates of the lower Tecuya Formation. To the west and north, the shelf deposits grade laterally into deep-marine shale of the Kreyenhagen Formation. The Middle and Upper Eocene San Emigdio Formation conformably overlies the Tejon Formation and records a second cycle of transgression and regression; this unit grades laterally northwestward into deep-marine shale (Nilsen *et al.*, 1973).

To the southeast of the San Joaquin basin, nonmarine deposits of the Goler and Witnet Formations may include Eocene strata, but appear to be chiefly of Paleocene age (Dibblee, 1967). In the Orocopia Mountains, Lower and Middle Eocene strata of the Maniobra Formation, 1460 m thick, rest unconformably on granitic and gneissic basement rocks (Crowell, 1975b). These marine deposits include a lower breccia and conglomerate, and an upper siltstone and sandstone that were probably deposited in a shallow-marine embayment that deepened offshore to the west.

West of the San Andreas Fault

In the Gualala area, the upper part of the thick lower Tertiary deep-sea-fan deposits of the German Rancho Formation of Wentworth (1968) record continued deposition into the Early and Middle Eocene. This fan complex was deposited in a northwest-trending basin by northwest-flowing turbidity currents. To the east-southeast of Point Reyes, Eocene deep-marine shale has been penetrated by offshore wells.

In the La Honda basin, Eocene strata are thick and generally of deep-marine character (Clark, 1981). The Butano Sandstone of Early and Middle Eocene age is possibly as thick as 3000 m, rests unconformably on the Paleocene Locatelli Formation, and was deposited as a deep-sea fan by north- and northeast-flowing turbidity currents (Nilsen, 1979b, 1985). It was derived from erosion of granitic basement rocks to the south in the Salinian block. The Butano Sandstone is conformably overlain by the San Lorenzo Formation of late Middle Eocene to Early Oligocene age (Clark, 1981); this unit is mostly a hemipelagic shale as thick as 900 m, deposited at bathyal depths. To the southeast, Lower to Upper Eocene strata that are about 1000 m thick crop out in the San Juan Bautista area (Nilsen, 1984c); these deposits include a shallow-marine basal conglomerate overlying crystalline basement, an overlying siltstone with interbedded turbidites deposited at bathyal depths, and an upper shallow-marine sandstone.

In the northern Santa Lucia basin, thick Eocene strata have been divided into the Reliz Canyon Formation, Church Creek Formation, and Berry Formation (Durham, 1974; Nilsen and Link, 1975; Poore *et al.*, 1977; Graham, 1978). The Reliz Canyon Formation consists of three members: (1) basal shallow-marine, transgressive deposits of the Upper Paleocene and Lower Eocene Junipero Sandstone Member, 55 m thick; (2) deeper-marine mudstone of the Lower Eocene Lucia Mudstone Member, 45–110 m thick; and (3) deep-sea-fan deposits of the

Middle Eocene The Rocks Sandstone Member, as thick as 440 m. The Rocks Sandstone was interpreted by Link and Nilsen (1980) to be a small sand-rich deep-sea fan deposited by northwest-flowing turbidity currents in a restricted basin; Seiders and Joyce (1984) have recognized submarine-canyon deposits cut into crystalline basement rocks in proximal parts of this unit.

The Reliz Canyon Formation is overlain conformably by the Church Creek Formation of Middle and Late Eocene age; it consists of thin-bedded turbidites, shale, and mudstone as thick as 450 m, deposited at outer-shelf to slope depths (Graham, 1978, 1979b). The Church Creek Formation interfingers southward and eastward with prograding fluvial redbeds of the lower part of the Upper Eocene and Oligocene Berry Formation (Graham, 1978).

In the Sierra Madre basin, the upper part of the thick fill of the basin includes Lower and Middle Eocene deposits that are well exposed in the Sierra Madre Range. The sequence consists mostly of deep-marine clastic rocks deposited in a restricted basin that shoaled northward, eastward, and southward (Chipping, 1972). In the Mount Pinos area, shallow-marine Lower Eocene strata as thick as 670 m rest unconformably on granitic basement.

Eocene strata of the Santa Ynez basin are thick and widespread. Lower Eocene deposits include the Sierra Blanca Limestone, 0–80 m thick, and deposited on the northern flank of the basin in algal-bank, shoreline, talus-slope, and related shallow-marine environments. The Juncal Formation conformably overlies the basal limestone deposits; it is as thick as 1060 m, consists of interbedded sandstone and shale deposited in shallow-marine environments to the east and north, and deep-marine environments to the south and west. Sediment transport was dominantly toward the southwest, where the Juncal grades laterally into deep-marine shale of the Anita Shale. Lower Eocene strata to the southeast include shallow-marine and nonmarine deposits of conglomerate, sandstone, and shale in the Santa Monica Mountains, Simi Hills, and Piru Creek area; to the south, deep-marine shale and sandstone crop out on Santa Rosa, San Miguel, and Santa Cruz Islands.

Middle Eocene deposits in the central Santa Ynez basin consist of the Matilija Sandstone, Cozy Dell Shale, Coldwater Sandstone, and lower part of the Gaviota Formation. The Matilija Sandstone is as thick as 840 m and records westward progradation of a sand-rich deep-sea fan over the Juncal Formation; it grades upward into shallow-marine and lagoonal deposits in its upper part, signaling the end of one cycle of basin filling (Link and Welton, 1982). The basin subsequently deepened and a second cycle of basin filling began with turbidite sedimentation in the upper part of the Matilija Sandstone (Ingle, 1980). The Cozy Dell Shale is as thick as 1200 m, was deposited mostly at bathyal depths, includes some thin-bedded turbidites transported to the southwest, and grades eastward.and northward into shallow-marine sandstone and conglomerate (Berman, 1979; Slatt and Thompson, 1985). The overlying Coldwater Sandstone is as thick as 760 m and consists of shallow-marine and deltaic deposits that prograded southwestward across the basin. In the western Santa Ynez basin, the Coldwater Sandstone grades laterally into turbidites of the Sacate Formation, about 300 m thick, deposited by west-flowing tubidity currents. The Gaviota Formation overlies the Coldwater and Sacate Formations in the western Santa Ynez Mountains; it is as thick as 530 m and its lower part consists of mudstone deposited at bathyal depths.

Middle Eocene deposits to the south and east in the Simi Hills, Piru Creek area, and Santa Monica Mountains consist generally of shallow-marine conglomerate and sandstone that define an irregular shoreline. To the south, Middle Eocene deposits in the Channel Islands consist of deep-marine shale and turbidite sandstone with variable paleocurrent directions (Bartling, 1981; Kies, 1982a).

The Upper Eocene deposits of the Santa Ynez basin include the upper part of the Gaviota Formation, various shallow-marine units, and the Sespe Formation, a thick fluvial sequence that records Late Eocene and Oligocene southwestward progradation of a complex fluvial system (McCracken, 1972).

In the Santa Ana Mountains, the Middle Eocene Santiago Formation rests with apparent unconformity on underlying Paleocene strata. It is as thick as 820 m and consists of a basal shallow-marine conglomerate and sandstone, a middle shallow-marine sandstone, and an upper fluvial conglomeratic sandstone.

Farther south in the western Peninsular Ranges, Eocene strata are abundant and generally rest unconformably on either crystalline basement or Cretaceous sedimentary strata (Eisenberg and Abbott, 1985). The Eocene sequence consists of two major transgressive-regressive cycles (May and Warme, this volume). Fluvial gravels and sands were transported westward across the Peninsular Ranges and grade offshore into deep-sea-fan deposits (Link *et al.,* 1979; Howell and Link, 1979).

The lower part of the Upper Paleocene to Upper Eocene sequence is assigned to the La Jolla Group and includes, in ascending order: (1) a basal transgressive shallow-marine, estuarine, alluvial-fan, submarine-canyon, and deep-sea-fan channel conglomerate and sandstone of the Upper Paleocene to Lower Eocene Mount Soledad Formation, 70 m thick (Kies, 1982b); (2) lagoonal and tidal-channel sandstone and mudstone of the Delmar Formation, 30–60 m thick (Clifton, 1979; Eisenberg, 1985; Irwin, 1985); (3) shallow-marine deposits of a sandy barrier-island system of the Torrey Sandstone, 60 m thick (Boyer and Warme, 1975; Irwin, 1985); (4) deep-marine deposits of the Ardath Shale, 70 m thick; (5) shallow-marine to deep-marine conglomerate, sandstone, and shale of the Scripps Formation, 65 m thick; and (6) fluvial deposits of the Friars Formation, 35 m thick. Lohmar *et al.* (1979) regrouped the upper part of the Torrey Sandstone, the Ardath Shale, and the Scripps Formation as the Rose Canyon Formation, an assemblage of shelf-edge deposits that includes submarine-canyon-head, lower-slope, inner-fan-channel, interchannel, and channel-margin facies. May *et al.* (1983) and May (1985) described these submarine-canyon deposits in detail and referred to the canyon complex as the Torrey Submarine Canyon.

A second cycle of sedimentation is recorded by the Upper Eocene Poway Group, which includes, in ascending stratigraphic order: (1) basal nonmarine deposits of the Stadium Conglomerate, 50 m thick; (2) shallow-marine conglomerate and sandstone of the Mission Valley Formation, 58 m thick; and (3) upper fluvial deposits of the Pomerado Conglomerate, 10 m thick. The entire group grades laterally eastward into fluvial and fan-delta deposits of the Ballena Gravels, as thick as 150 m (Minch, 1979; Howell and Link, 1979).

The Eocene strata are marked by prominent paleosols developed at the base of the section as well as within the section at the top of the Mount Soledad Formation. The paleosols suggest a warm and humid climate indicative of tropical lateritic weathering within the Paleocene and through the Middle Eocene (Peterson and Abbott, 1981). Younger paleosols characterized by caliche horizons within the Friars Formation and Mission Valley Formation indicate subsequent return to arid conditions in the Late Eocene (Peterson and Abbott, 1977).

The Eocene strata in the San Diego area contain a distinctive suite of resistant, reddish-weathering, rhyolitic and dacitic porphyries that were transported by west-flowing streams from a distinctive source area in Sonora, Mexico (Minch *et al.,* 1976; Abbott and Smith, 1978; Link and Howell, 1979; Minch, 1979). This suite of clasts, the Poway clasts, can be recognized in many parts of southern California and permits restoration of deep-sea fans, shallow-marine deposits, and fluvial deposits that are presently widely dispersed.

In the Southern California Borderland, Middle Eocene deep-sea-fan deposits as thick as 1050 m crop out on San Nicolas Island. Paleocurrents indicate sediment transport to the south-southwest, and sandstone composition suggests derivation from a granitic source area that included metavolcanic rocks (Cole, 1977).

Eocene Paleogeography and Paleotectonics

The Eocene Epoch was clearly complex and involved major tectonic reorganization of California (Fig. 5-10). Major uplift occurred in the Klamath Mountains, resulting in the deposition of coarse-grained fluvial deposits to the northeast; initial formation of the Cascade volcanic arc is recorded in coarse-grained volcanogenic Eocene conglomerates farther south. The Sierra Nevada also underwent major uplift, recorded by fluvial and deltaic deposits along its western flank and by auriferous fluvial gravels within the range and at the northern margin of the range. Additional uplifts took place in parts of the Coast Ranges west of the Sacramento basin, although continued subduction farther west resulted in deposition, accretion, and deformation of the coastal belt of the Franciscan Complex as part of a subduction complex, and deposition of the Yager Formation in a probable trench-slope-basin setting.

The Sacramento basin underwent a complex depositional and deformational history caused by uplifts around the margins of the basin, syndepositional faulting within the basin, and major episodes of submarine-canyon cutting and filling related to relative changes in sea level. It generally deepened toward the southwest, where the thickest sections of Eocene strata are preserved. Turbidite sands transported down the canyon systems appear to have been deposited on deep-sea fans in the San Francisco Bay region; these fans are partly preserved in scattered, fault-bounded outcrops that have been dispersed by Neogene strike-slip faulting.

The Stockton arch generally formed a positive feature that separated the Sacramento basin from the San Joaquin basin. The San Joaquin basin generally records southward and westward deepening, with sediment supplied chiefly by the Sierra Nevada. A Lower Eocene deep-sea fan, fed by a west-trending submarine canyon, was deposited in the Vallecitos area along the western flank of the basin. Major uplift and deformation, resulting in the exposure of Franciscan basement, took place in Early to Middle Eocene time along the western margin of the basin. Accretion of the Salinian block in Early Eocene time resulted in the deposition of two deep-sea fans that spilled across the suture into the San Joaquin basin.

Palinspastic restoration of Neogene fault offsets and rotations provides a better framework for understanding the paleogeographic and paleotectonic framework of central and southern California (Fig. 5-11). Suturing of the Salinian block and Sur-Obispo terrane resulted in the formation of a tectonically active and mobile borderland in which deep-sea fans were deposited in small restricted, but deep basins, such as the Gualala basin, La Honda basin, northern Santa Lucia basin, Sierra Madre basin, and Santa Ynez basin (Fig. 5-12). Restoration of 315 km of Neogene offset along the San Andreas fault restores: (1) the Butano fan of the La Honda basin with the Point of Rocks fan of the Temblor Range (Clarke and Nilsen, 1973); (2) similar transgressive basal conglomerate and overlying basin-plain turbidites of the San Juan Bautista area and western San Emigdio Range (Nilsen, 1984c); and (3) Eocene deposits of the Maniobra Formation in the Orocopia Mountains with similar strata in the Piru Creek area of the eastern Santa Ynez basin (Howell, 1975b).

Accretion of the Salinian composite terrane also may have caused rotation and oroclinal bending of the southern end of the Sierra Nevada batholith, Tehachapi Mountains, and San Emigdio Mountains. Initial rotation of about 20°

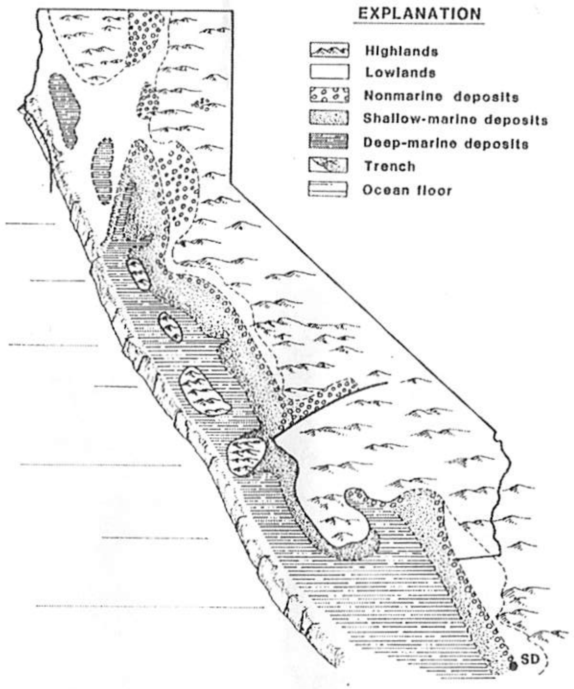

Fig. 5-11. Restored Eocene paleogeographic map of California. The paleogeographic elements are shown in their Eocene locations and orientations.

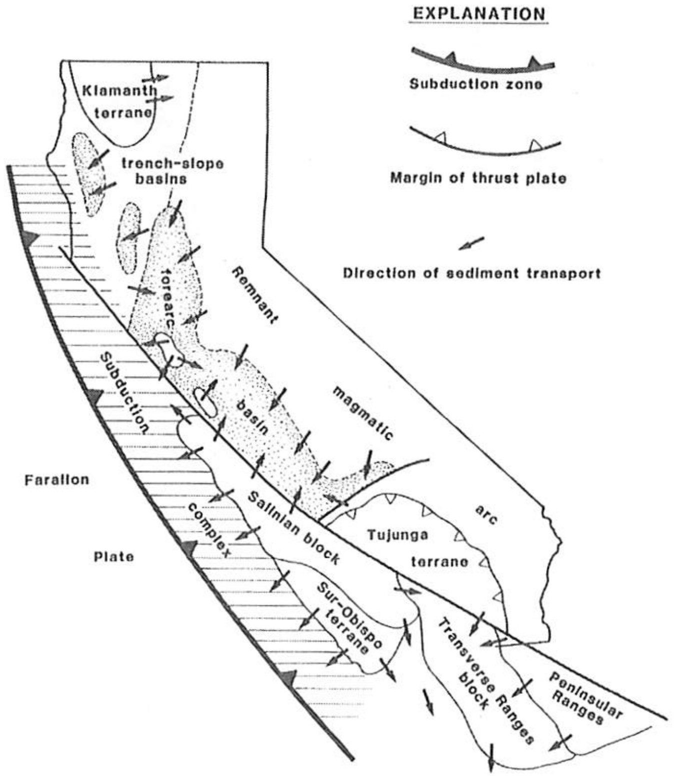

Fig. 5-12. Eocene paleotectonic map of California. The generalized paleotectonic elements are shown in their Eocene locations and orientations.

could have occurred at the end of the Paleocene, prior to larger Neogene rotations in the Transverse Ranges (McWilliams and Li, 1985). Northeastward thrusting of the Tujunga terrane onto the Mojave Desert province and San Gabriel Mountains area, as postulated by Vedder *et al.* (1983) and Howell *et al.* (this volume), was probably also related to accretion of the Salinian composite terrane. Unusual allochthonous gabbroic rocks in the western San Emigdio Range and San Juan Bautista areas (Ross, 1970, 1984) also may have been thrust eastward during this accretionary event. The thrusting resulted in a topographically high region in, and adjacent to, the Mojave Desert province; only in the late Early Eocene and Middle Eocene were subsiding parts of the southern San Joaquin basin, San Emigdio Range, western Tehachapi Mountains, and Orocopia Mountains transgressed by Eocene seas. The Goler and Witnet basins, neither of which contain well-dated deposits, may have formed in response to accretion or, alternatively, may have been subjected to major uplift in Early Eocene time.

The Transverse Ranges block and Peninsular Ranges block also may have accreted to California at this time, but at a more southerly latitude (Hagstrum *et al.*, 1985; Howell *et al.*, this volume). These blocks appear to preserve, when the Transverse Ranges block is rotated back to a pre-Miocene north-south orientation, a fragment of a magmatic-arc/forearc-basin/subduction-complex system (Fig. 5-12). However, the postulated forearc basin has been displaced and slivered by Neogene strike-slip faulting along the East Santa Cruz basin and other faults, and by the accretion of additional terranes in the Southern California Borderland, as outlined by Howell *et al.* (this volume). Cretaceous deep-sea-fan deposits from south of the San Diego area have been displaced to San Miguel Island, and Eocene deep-sea-fan deposits from San Miguel Island containing Poway clasts have been displaced from the San Diego area (Bartling and Abbott, 1983); these displacements were initiated in Paleocene time, possibly synchronously with northward movement of either the Salinian composite terrane or displacement of the southern extension of the Great Valley forearc basin.

Abbott *et al.* (1983) and Howell and Vedder (1985) provided reconstructions of a large Eocene deep-sea fan composed of Poway clast-bearing turbidites in the San Diego area, San Miguel Island, Santa Rosa Island, southern Santa Cruz Island, and San Nicolas Island. The reconstructed fan is about 400 km long, 40–100 km wide, and at least 1000 m thick; the main body of the fan was originally located south of the San Diego area and was deposited by turbidity currents that flowed south-southeastward from its apex and source near San Diego.

OLIGOCENE BASINS

During the Oligocene Epoch, California was dominated by nonmarine sedimentation, in contrast to the preceding early Tertiary and succeeding Neogene intervals in which marine sedimentation was dominant. The change to nonmarine conditions can be attributed to tectonic uplift related to the approach of the Pacific-Farallon spreading ridge and initiation of a transform margin (Nilsen, 1984a), continued cooling and increased aridity that began in the Late Eocene (Peterson and Abbott, 1979), and a major eustatic lowering of sea level, possibly by as much as 350 m, in mid-Oligocene time, about 30 my B.P. (Fig. 5-4; Vail *et al.*, 1977a). Because of the abundance of poorly dated Oligocene nonmarine sequences, the presence of numerous unconformities at the base, within, and at the top of many Oligocene sequences, and the lack of well-dated volcanic rocks within Oligocene sequences, biostratigraphic zonations and correlations with absolute time for the Oligocene are not as well defined as they are for older and younger marine-dominated sections. The Zemorrian stage is equivalent to almost the entire Oligocene Epoch, 37–24 my B.P. (Poore, 1980; Fig. 5-4).

Oligocene rocks are widely distributed in California and were deposited in many separate basins (Fig. 5-13). They are most abundant and thickest in the southern Coast Ranges, Transverse Ranges, and southern San Joaquin Valley. The most common lithologic association, particularly in southern California, consists of nonmarine conglomerate, sandstone, and mudstone, herein referred to as redbed sequences (Fig. 5-14). The second common association, particularly in northern California, consists of shallow- and deep-marine clastic rocks, primarily sandstone and shale. The least common association consists of dominantly subaerial felsic, intermediate, and mafic volcanic rocks, which are generally of latest Oligocene age, and were extruded mostly in upland parts of the Sierra Nevada, Mojave Desert, and Coast Range provinces. Oligocene rocks have not been reported from the Modoc Plateau, which is completely covered by Neogene volcanic rocks, or from the Salton Trough, which formed in Neogene time as a result of the opening of the Gulf of California.

Fig. 5-13. Map of California showing general location of Oligocene basins and outcrops of Oligocene rocks. The basins and outcrops are shown in their present locations.

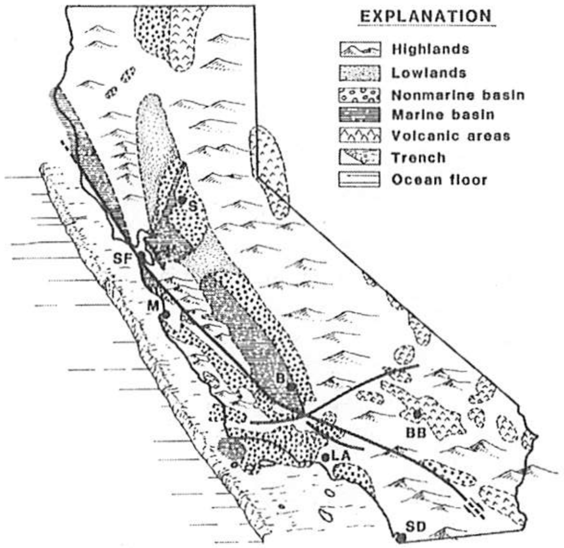

Fig. 5-14. Unrestored Oligocene paleogeographic map of California. The paleogeographic elements are shown in their present locations and orientations.

The distribution of Oligocene basins in California, compared to that for the Late Cretaceous and early Tertiary, clearly signals the development of numerous new basins as a result of changing tectonic framework (Fig. 5-13). Many of these basins, such as those in the Mojave Desert, Los Angeles, and Southern California Borderland areas, became more fully developed in the Miocene, when continued transform movement led to the development of deep, petroliferous basins (Blake *et al.,* 1978; Howell *et al.,* 1980). Other basins, such as the Sacramento and San Joaquin, continued to develop in Oligocene time.

East of the San Andreas Fault

In the Cascade Range of northern California, volcanic rocks of the Upper Oligocene and Lower Miocene Western Cascades Group overlie, with a regional low-angle unconformity, Cretaceous marine strata of the Hornbrook Formation (Vance, 1984). The Oligocene sequence consists mostly of basaltic lava flows, andesitic mudflows, and fluvial volcanogenic deposits that were erupted and deposited mostly in the Late Oligocene, between 31 and 25 my B.P. The sequence, about 1550 m thick, was deposited on an alluvial and volcanic plain of low relief that had a westerly paleoslope; the Oligocene Cascade arc, with andesitic stratovolcanoes, lay to the east. Angular unconformities within the Western Cascades Group indicate episodes of warping and uplift during deposition.

In the southern Klamath Mountains, nonmarine strata of the Weaverville Formation, which on the basis of plant fossils are at least partly of Oligocene age, rest unconformably on metamorphic basement rocks (Irwin, 1966). The Weaverville Formation is about 600 m thick and consists of auriferous conglomerate, sandstone, shale, lignite, and tuff deposited in fluvio-lacustrine environments.

In the northwestern Coast Ranges, marine sedimentary and volcanic rocks that probably include Oligocene strata continued to accumulate and be deformed as part of the subduction-related coastal belt of the Franciscan Complex (Bachman, 1978, 1982; Bachman and Crouch, this volume). The Yager Formation may be as young as Oligocene, and thus, record Oligocene trench-slope-basin sedimentation on older deformed rocks of the Franciscan Complex (Underwood, 1983). Extensive deformation and uplift may have characterized the northwestern Coast Ranges during the Oligocene, because both the Yager Formation and the coastal belt of the Franciscan Complex are overlain with angular unconformity by Middle Miocene and younger strata of the Wildcat Group (Bachman *et al.,* 1984).

The northern part of the Sacramento basin had been largely infilled by Oligocene time and formed a broad fluvial plain of low relief that had a southwesterly paleoslope (Hackel, 1966). The southern part of the basin formed a broad marine shelf dissected by Markley Gorge, a southwest-trending submarine canyon at least 130 km long, 9–12 km wide, and at least 760 m deep (Almgren and Schlax, 1957; Almgren, 1978; Pepper-Kittridge and Wilson, 1984). The gorge was cut in latest Eocene time and filled during the Oligocene at bathyal depths and during the Early Miocene at neritic depths; numerous stratigraphic traps, from which gas has been produced, are associated with Markley Gorge (Nahama and Weagant, 1984). The gorge fill consists mostly of shale, with minor amounts of sandstone and conglomerate, derived partly from andesitic and basaltic volcanic rocks that were erupted locally in the northwestern and western Sierra Nevada (Dalrymple, 1964; Durrell, 1966). At the northeastern end of the gorge, shallow-marine strata of the Oligocene Wheatland Formation of Clark and Anderson (1938), that are about 100 m thick, crop out along the western flank of the Sierra Nevada. At the southwestern edge of the Sacramento basin, various thin deep-marine sandstone and shale units crop out in the San Francisco Bay region, and have been offset and displaced along Neogene strike-slip faults of the San Andreas fault system.

In the San Joaquin basin, Oligocene strata are generally thick and abundant; they crop out extensively along the western, southern, and eastern margins of the basin. There is generally a gradation southward from the Stockton arch and westward from the southwestern flank of the Sierra Nevada toward the basin center from redbeds and shallow-marine deposits to deep-marine deposits.

Along the western flank of the San Joaquin basin, Oligocene strata of the lower Temblor Formation that are as thick as 165 m rest unconformably on Cretaceous to Eocene rocks (Dibblee, 1973b; Carter, 1985; Pence, 1985). The Temblor Formation thins northward toward the Stockton arch, where it was deposited in shallow-marine and nonmarine environments; here, it was derived from erosion of uplifted parts of the central Coast Ranges (Bent, 1985). In the subsurface to the north, the Temblor Formation grades laterally into the nonmarine, informally designated Zilch formation and southern fluvial deposits of the Valley Springs Formation (Bartow, this volume). Farther north, Oligocene strata are generally absent from the Stockton arch, which was exposed subaerially during the Oligocene (Bartow, 1985a).

Along the eastern and southern flanks of the San Joaquin Valley, west-transported redbeds of the Walker Formation, Bealville Conglomerate, and Tecuya Formation interfinger westward and northwestward in subsurface and outcrop with shallow-marine rocks (Nilsen *et al.,* 1973; Bartow and McDougall, 1984). In the southeastern corner of the San Joaquin basin, the Oligocene redbeds are much coarser than farther north, and were deposited as alluvial fans that were shed northwestward into the basin, in part controlled by uplifts along active faults (Bartow, this volume).

The central parts of the San Joaquin basin, especially the south-central portions, remained deep and received chiefly turbidite and hemipelagic deposits derived from northern, eastern and southern sources (Bent, 1985). Various formal and informal stratigraphic names have been applied to these subsurface units, including the Temblor Formation, Pleito Formation, Vedder Formation, Santos shale, and Whepley shale (Bent, 1985). They were deposited in bathyal or deeper environments (Bandy and Arnal, 1969; Tipton *et al.,* 1973), and large amounts of petroleum have been produced from them (Adkison, 1973).

In the Mojave Desert province, poorly dated middle Tertiary nonmarine sedimentary and volcanic rocks that rest on Paleozoic and Mesozoic crystalline basement rocks crop out in various areas. Although these deposits are chiefly of Miocene age, some redbeds and volcanics of latest Oligocene age are probably present in the basal parts of some basins. The volcanic rocks range in composition from rhyolite to basalt, and include pyroclastic rocks, volcanic breccias, and volcanic flows (Woodburne *et al.,* 1982). Some local quartz monzonites and dike swarms may also be of Oligocene age (Dibblee, 1980b). Dibblee (1977) delineated two east-west-trending basins in the province, the Barstow basin to the east and Kramer basin to the west.

The Kramer basin consists mostly of tuff-breccia that is about 620 m thick to the west and 310 m thick to the east (Dibblee, 1980b). The Barstow basin contains a lithologically more variable sequence, as thick as 5800 m, that includes lacustrine, fluvial, and alluvial-fan deposits in addition to volcanic rocks (Link, 1980); radiometric dating of the oldest volcanic rocks, however, has yielded an Early Miocene age of 23.1 ± 0.2 (Burke *et al.,* 1982). The Barstow basin may have developed initially along a system of listric normal faults that were later obscured and rotated by strike-slip faulting (Burke *et al.,* 1982; Dokka and Glazner, 1982).

In the Diligencia basin, 1500 m of Oligocene and Lower Miocene redbeds of the Diligencia Formation of Crowell (1975b) unconformably overlie marine Middle Eocene strata and gneissic basement rocks of the Orocopia Mountains. The Diligencia Formation consists of conglomerate, sandstone, mudstone, volcanic flows and sills, and minor amounts of sedimentary breccia, limestone, gypsum, and other evaporites; Late Oligocene or Early Miocene vertebrate remains were recovered from 365 m above the base of the sequence (Woodburne and Whistler, 1973). The basin appears to have developed as an intramontane east-west-trending graben bounded by normal faults; coarse debris was transported northeastward and southward into the basin, interfingering with lacustrine deposits (Crowell, 1975b; Bohannon, 1975).

In the Chocolate Mountains and Whipple Mountains of southeastern California, potassium-argon dates of Oligocene age have been obtained from calc-alkaline volcanic rocks erupted in north- and northwest-trending, fault-controlled basins (Crowe, 1978; Crowe *et al.,* 1979; Korsch, 1979; Murray, 1982; Davis *et al.,* 1982). However, some of the ages may have been reset by postextrusive thermal events related to detachment faulting (Martin *et al.,* 1982). In northwestern Mexico east of the Gulf of California, west-transported fluvial deposits, local basalt flows, and rhyolite ash of Oligocene age are present (Gastil *et al.,* 1979).

West of the San Andreas Fault

In the La Honda basin, Oligocene strata are thick and consist, in ascending stratigraphic order, of: (1) the upper part of the San Lorenzo Formation, hemipelagic mudstone with some thin-bedded basin-plain turbidites; (2) the Vaqueros Formation, a deep-sea-fan complex as thick as 1400 m that was deposited by northward-flowing turbidity currents; (3) the Mindego Basalt, pillow lava, flow breccia, and lithic tuff as thick as 1200 m that was deposited in shallow-marine and subaerial environments; and (4) the lower part of the Lambert Shale, hemipelagic shale that is locally semisiliceous and phosphatic (Clark, 1981; Stanley, 1984). Along the southern margin of the basin, the Zayante Sandstone crops out and interfingers northward with shallow- to deep-marine strata of the upper part of the San Lorenzo Formation and the Vaqueros Formation; the Zayante Formation is as thick as 550 m and was deposited as an alluvial-fan complex shed northward off an active west-northwest-trending fault (Clark, 1981). The La Honda basin may extend discontinuously southeastward along the San Andreas fault to the north edge of the Gabilan Range, where similar nonmarine and marine strata crop out (Clark and Rietman, 1973); an alluvial-fan complex that is 1200 m thick in this area was shed northward off an active west-northwest-trending fault.

In the northern Santa Lucia Range, shallow-marine sandstone and mudstone of the Vaqueros Formation rest unconformably on lower Tertiary strata (Graham, 1978, 1979b). The Vaqueros Formation is about 500 m thick, and was deposited in deltaic, tidal-channel, and barrier-bar settings.

In the San Luis Obispo area, volcanic and sedimentary rocks crop out in several areas. The Morro Bay-Islay Hill complex extends westward from San Luis Obispo and consists of dacite volcanic plugs, lava domes, intrusive sheets, and felsic rocks that have yielded potassium-argon ages of 22.1 ± 0.9 and 26.5 ± 0.8 my (Turner, 1968; Turner *et al.,* 1970). The Cambria Felsite crops out about 50 km north of San Luis Obispo, is about 115 m thick, and consists of subaerially deposited rhyolitic and dacitic tuff (Ernst and Hall, 1974). The Cambria Felsite is unconformably overlain by nonmarine conglomeratic strata of the Lospe Formation, which is 150–200 m thick; the Lospe is gradationally overlain by shallow-marine deposits of the Vaqueros Formation (Ernst and Hall, 1974). Other scattered outcrops of Oligocene marine and nonmarine strata that rest unconformably on Cretaceous strata are present in the San Luis Obispo area (Hart, 1976).

In the Caliente basin, nonmarine conglomerate and sandstone of the Simmler Formation are overlain conformably by shallow-marine strata of the lower part of the Vaqueros Formation. The Simmler Formation is about 1000 m thick, and consists of alluvial-fan, fluvial, and lacustrine deposits that were shed northward and northeastward into the basin (Bartow, 1978; Ballance *et al.,* 1983; Ballance, 1984).

In the Santa Maria basin, Oligocene nonmarine strata of the Lospe Formation rest unconformably on the Great Valley Group and Franciscan Complex, and are overlain unconformably by shallow-marine strata of the Vaqueros Formation (Hall, 1981b). The Lospe Formation extends offshore (Hoskins and Griffiths, 1971), and was derived chiefly from erosion of the Franciscan Complex (Anderson, 1980).

In the Santa Ynez basin, nonmarine redbeds of the Sespe Formation form a thick and widespread sheet that records the last stages of basin filling (McCracken, 1972). The Sespe Formation is as thick as 1700 m, and was deposited chiefly by west-flowing streams that drained highlands to the north underlain by the Franciscan Complex and highlands to the east underlain by granitic rocks. The Sespe Formation unconformably overlies older strata along the northern and eastern margins of the basin, and conformably overlies and locally interfingers with Upper Eocene and Lower Oligocene shallow-marine strata in the central and western parts of the basin. The Sespe Formation is more than 1000 m thick in the Santa Monica Mountains (Yerkes *et al.,* 1965; Campbell and Yerkes, 1976), and absent from the Channel Islands except on Santa Rosa Island, where 150 m of north-transported fluvial deposits crop out (McCracken, 1972).

In the Soledad basin, nonmarine strata of the Vasquez Formation were deposited in three separate and narrow, east-west-trending, fault-bounded basins (Bohannon, 1976; Hendrix, 1986). The Vasquez Formation unconformably overlies lower Tertiary turbidites and is unconformably overlain by nonmarine Lower Miocene strata. Volcanic flows that are 23–26 my old are present in the lower part of the formation (Terres *et al.,* 1981). The northern basin was filled by alluvial fans shed westward and northward into the basin, the central basin by alluvial fans shed northwestward and southward toward the basin axis, and the southern basin by alluvial fans shed northwestward and northward into the basin, interfingering with lacustrine deposits (Bohannon, 1976; Hendrix, 1986).

In the Los Angeles basin, Oligocene strata consist of the lower nonmarine Sespe Formation and the upper shallow-marine Vaqueros Formation (Yerkes *et al.,* 1965; Schoellhamer *et al.,* 1981; Mayer, this volume). The strata are thick and well exposed on the southeastern margin of the basin, underlie most of the central part of the basin, and are absent along the northwestern and southwestern margins of the basin. The Oligocene units rest unconformably on lower Tertiary marine strata and are overlain unconformably by Middle Miocene strata. The Sespe Formation is as thick as 800 m and consists mostly of conglomerate and sandstone derived from the southeastern margin of the basin. The Vaqueros Formation is as thick as 1200 m, consists primarily of sandstone and siltstone, and records northwestward deepening of the basin from its southeastern margin in the Santa Ana Mountains.

In the Southern California Borderland, the distribution of Oligocene strata is poorly known. Marine strata as thick as 450 m have been penetrated in offshore test wells in a northwest-trending belt adjacent to San Nicholas Island, but appear to be thin or absent in adjacent parts of the borderland to the east and west (Howell and Vedder, 1981).

Oligocene Paleogeography and Paleotectonics

Oligocene strata were deposited in separate basins that contain both nonmarine and marine strata (Fig. 5-14). The basins include many that persisted from earlier times, although they are generally smaller and more subaerial in character, and new basins that developed in response to a changing tectonic framework. Marine strata are generally more common in central and western California, and nonmarine strata in northern, southern, and eastern California. Volcanic rocks are scattered, but most common in eastern California and some parts of the Coast Ranges; they are generally of Late Oligocene age and became more abundant toward the close of the epoch.

The distribution of the Oligocene highlands and lowlands, areas of marine and nonmarine sedimentation, and volcanic centers is complex prior to palinspastic restoration (Fig. 5-14). East of the San Andreas fault, the Franciscan subduction complex records the continued presence of a convergent margin in northern California and, if similar rocks continue southward along the base of the continental slope, possibly all of western California. The Stockton arch became more prominent, completely separating the Sacramento and San Joaquin basins. New basins and volcanic centers developed in the western and central Mojave Desert province. The Goler and Witnet basins became inactive. The Diligencia basin developed in an area previously covered partly by Eocene shallow-marine deposits.

West of the San Andreas fault, the La Honda, Salinas, and Caliente basins persisted from the Eocene, although considerably changed by uplift along basin margins and the development of subbasins by faulting. The names "Salinas" and "Caliente" basins supplant the names "northern Santa Lucia" and "Sierra Madre" basins, respectively, for the broader and differently shaped early Tertiary basins. Numerous smaller Eocene basins, filled primarily by turbidite sequences, did not persist into the Oligocene. Little evidence exists for the presence of Oligocene basins in the Salinian block north of San Francisco. West of the Salinian block, the Santa Maria basin began to develop as a small feature in which a thin sequence of redbeds was deposited, and new volcanic centers developed in the San Luis Obispo area.

In southern California, the Santa Ynez basin persisted into the Oligocene and the Soledad basin developed as a series of separate fault-bounded subbasins. Oligocene redbeds were deposited along the southeastern margin of the Los Angeles basin, which developed more fully in the Miocene. Oligocene rocks are absent in the Peninsular Ranges province and present in only the central part of the Southern California Borderland, although the configuration of possible Oligocene basins in this area compared to pre-Oligocene basins is still unknown.

Palinspastic reconstruction of the Oligocene paleogeography of California by removing major strike-slip displacements restores the Franciscan subduction complex to a single belt, connects the La Honda basin and southwestern San Joaquin basin, and forms a single basin of the Salinas, Caliente, Soledad, and Diligencia basins (Fig. 5-15). Calc-alkaline andesitic, dacitic, and rhyolitic volcanic rocks of the Pinnacles and Neenach areas, which have yielded potassium-argon ages of 23.5 my (Turner, 1970) near the Oligocene-Miocene boundary, are also restored to a single volcanic complex (Matthews, 1976).

Additional reconstruction by restoring major rotations in southern California results in the Salinas-Caliente-Soledad-Diligencia basin forming a west-northwest-trending northern half and a north-south-trending southern half (Fig. 5-15). The Santa Ynez basin formed a separate north-south-trending basin either east of or south of the Salinas-Caliente-Soledad-Diligencia basin. Pre-Miocene southward restoration of the Transverse Ranges by 5–15° (Luyendyk and Hornafius, this volume) and the Peninsular Ranges by less than 11° (Hagstrum *et al.*, 1985) is compatible with Crouch's (1979b) model for northward translation and rotation of the Transverse Ranges block in the Miocene and Truex's (1976) determination that Oligocene strata of the Santa Ana Mountains, Santa Monica Mountains, and Santa Ynez Mountains originally formed a single large basin.

The Oligocene tectonic framework (Fig. 5-16) was dominated initially by subduction of the Farallon plate at an increasing angle of descent, as convergence rates between it and the North American plate systematically decreased through mid-Cenozoic time (Keith, 1978). Westward migration of calc-alkaline volcanism into eastern California in the western Cascade Range, Sierra Nevada, and Mojave Desert provinces took place simultaneously (Dickinson, 1979; Nilsen and McKee, 1979). Interaction between the Pacific and North American plates that began in mid-Oligocene time initiated development of a transform margin, and eventual

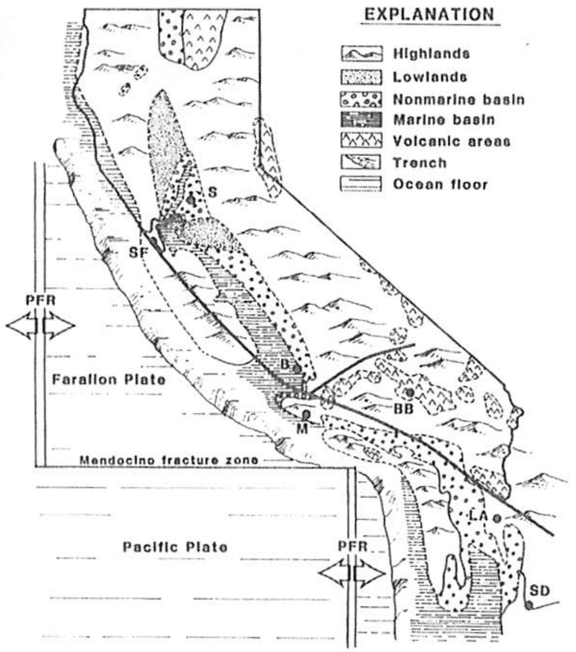

Fig. 5-15. Restored Oligocene paleogeographic map of California. The paleogeographic elements are shown in their Oligocene locations and orientations.

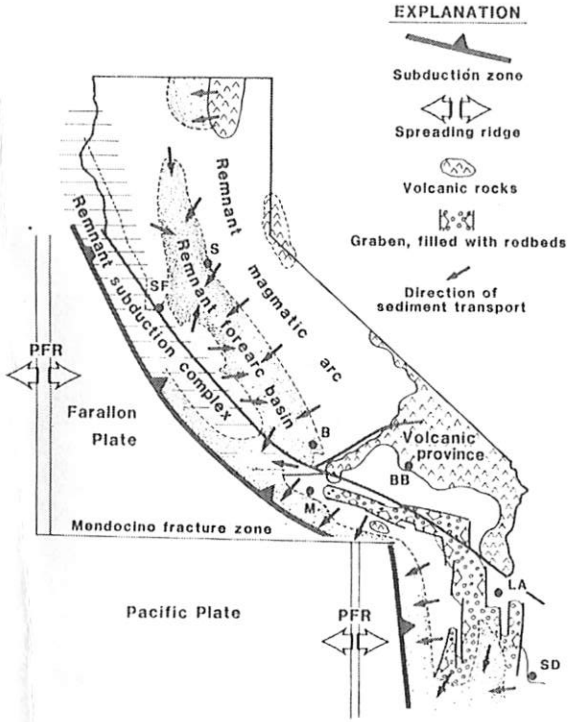

Fig. 5-16. Oligocene paleotectonic map of California. The generalized paleotectonic elements are shown in their Oligocene locations and orientations.

northward and southward cessation of arc volcanism and migration of triple junctions in the Neogene (Blake *et al.*, 1978).

The regional distribution of nonmarine Oligocene basins and uplifted areas suggests that tectonic uplift of the southwestern United States, rather than coincident eustatic sea-level or climatic changes (which would have had a more uniform and widespread effect), was the chief controlling factor. The approach of the Pacific-Farallon spreading ridge and Mendocino fracture zone to the southern California margin, and their resultant interaction with the margin, was probably responsible for the regional uplift and development of subaerial north-south-trending grabens (Nilsen, 1984a).

The hot, young buoyant oceanic crust at the spreading ridge probably uplifted and fractured the continental margin, partly along the edges of previous Late Cretaceous and early Tertiary basins, but also along new faults. The new faults trended north-south in the region directly east of the spreading ridge and west-northwest in the area north of, and marginal to, the triple junction. Thus, extensive redbed sedimentation may have resulted from the impingement of a large spreading ridge onto previously fractured and broken crust. The crescent-shaped paleogeographic distribution of Oligocene nonmarine basins in southern California (Fig. 5-16) may have developed marginal to the triple junction and spreading ridge. Subduction and northward migration of the Mendocino fracture zone, which may have formed a large topographic step in the subducting Farallon plate, may also have affected the distribution of Oligocene and Miocene fluvial sedimentation (Glazner and Loomis, 1984). Volcanism persisted to the north in the northern Mojave Desert, Sierra Nevada, Basin and Range, and western Cascade Range provinces as a result of continued subduction of the Farallon plate. The Cambria-San Luis Obispo volcanic rocks may have been generated close to the triple junction along the continental margin.

SUMMARY AND CONCLUSIONS

Paleogene sedimentation in California was strongly affected by syndepositional tectonism, climatic changes and sea-level changes. Tectonism was most important in controlling sedimentation in mobile areas such as the Salinian block, Transverse Ranges block, Southern California Borderland, and uplifted regions such as the Klamath Mountains, Sierra Nevada, and Mojave Desert provinces. Although plutonism had largely terminated in California by Paleogene time, the late Mesozoic batholithic complexes continued to be uplifted during the Paleogene, when they formed the major source areas for sedimentation to the west. By Late Oligocene time, renewed volcanism began to supply abundant volcaniclastic sediments in many parts of California; in northern California, volcaniclastic sediments derived from the ancestral Cascade volcanic arc began to appear earlier, in the Late Eocene.

Demonstrable faulting beneath the Sacramento basin, along the north flank of the Stockton arch, and in the Mount Diablo area, as well as major uplifts of the Franciscan Complex and associated Paleogene outliers along the western margin of the Sacramento basin, and southward tilting of the basin are indicative of tectonic control of sedimentation in northern California. In the San Joaquin basin, major uplifts on the west flank of the basin to expose the Franciscan Complex, strong Paleogene folding, and angular unconformities record active tectonism. Active faulting controlled the deposition of coarse nonmarine clastics in the Goler and Witnet basins.

Detachment, dispersion, and accretion of exotic terranes in the Paleocene and Early Eocene caused additional deformation. The Paleocene stratigraphic record preserved in these blocks suggests the formation of small, restricted, deep-marine basins surrounded by highlands; these basins and highlands appear to have developed during major northward translation of allochthonous terranes, probably caused by transtension and transpression. Accretion of the blocks locally yielded deposition of deep-sea fans into the western San Joaquin basin from source areas in the Salinian block.

Oligocene nonmarine deposition was strongly controlled by regional uplift related to the approach of the Pacific-Farallon spreading ridge and Mendocino fracture zone to the southwestern margin of California. Active faulting controlled the deposition of widespread fanglomerates in various types of Oligocene extensional basins, in almost every case, long before the large eustatic fall in sea level in the mid-Oligocene.

However, there were many relatively stable areas where the effects of global changes in sea level can be observed in the Paleogene record of California. In the Peninsular Ranges block, where Cretaceous and younger strata have been deformed to only a minor extent, the effects of eustatic changes in sea level on Eocene sedimentation are demonstrable (May and Warme, this volume). Similarly, in parts of the San Joaquin basin, which has been relatively stable along its northern and eastern margins, the controlling effects of eustatic sea-level changes are clear (Bartow, this volume). In the eastern Sacramento basin, another relatively stable area, changes in sea level can be unambiguously correlated with the cutting and filling of major submarine canyons (Almgren, 1978). In some of these stable areas, climatic cycles have also been demonstrated by various workers to have had an important control over sedimentation.

Within the stratigraphic sequences of some smaller basins within the Salinian block and Transverse Ranges, there are also some apparent correlations of sedimentation cycles to global sea-level changes; however, these are not always well dated and may in some cases be an expression of wishful thinking. As also demonstrated by geohistory analyses (Dickinson *et al.*, this volume) and evaluations of petroleum potential (Graham, this volume) of California basins, regional tectonism appears to be the chief controlling factor on cycles and patterns of sedimentation.

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