The Cenozoic Evolution of the San Joaquin Valley, California

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[Plates are in pocket]

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By J. Alan Bartow

ABSTRACT

The San Joaquin Valley, which is the southern part of the 700-km-long Great Valley of California, is an asymmetric structural trough that is filled with a prism of upper Mesozoic and Cenozoic sediments up to 9 km thick; these sediments rest on crystalline basement rocks of the southwestward-tilted Sierran block. The San Joaquin sedimentary basin is separated from the Sacramento basin to the north by the buried Stockton arch and associated Stockton fault. The buried Bakersfield arch near the south end of the valley separates the small Maricopa-Tejon subbasin at the south end of the San Joaquin basin from the remainder of the basin. Cenozoic strata in the San Joaquin basin thicken southeastward from about 800 m in the north to over 9,000 m in the south.

The San Joaquin Valley can be subdivided into five regions on the basis of differing structural style. They are the northern Sierran block, the southern Sierran block, the northern Diablo homocline, the west-side fold belt, and the combined Maricopa-Tejon subbasin and south-margin deformed belt. Considerable facies variation existed within the sedimentary basin, particularly in the Neogene when a thick section of marine sediment accumulated in the southern part of the basin, while a relatively thin and entirely nonmarine section was deposited in the northern part. The northern Sierran block, the stable east limb of the valley syncline between the Stockton fault and the San Joaquin River, is the least deformed region of the valley. Deformation consists mostly of a southwest tilt and only minor late Cenozoic normal faulting. The southern Sierran block, the stable east limb of the valley syncline between the San Joaquin River and the Bakersfield arch, is similar in style to the northern part of the block, but it has a higher degree of deformation. Miocene or older normal faults trend mostly north to northwest and have a net down-to-the-west displacement with individual offsets of as much as 600 m. The northern Diablo homocline, the western limb of the valley syncline between the Stockton arch and Panoche Creek, consists of a locally faulted homocline with northeast dips. Deformation is mostly late Cenozoic, is complex in its history, and has included up-to-the-southwest reverse faulting. The west-side fold belt, the southwestern part of the valley syncline between Panoche Creek and Elk Hills and including the southern Diablo and Temblor Ranges, is characterized by a series of folds and faults trending slightly oblique to the San Andreas fault. Paleogene folding took place in the northern part of the belt; however, most folding took place in Neogene time, during which the intensity of deformation increased southeastward along the belt and southwestward toward the San Andreas fault. The Maricopa-Tejon subbasin and the south-margin deformed belt are structurally distinct, but genetically related, regions bounded by the Bakersfield arch on the north, the San Emigdio Mountains on the south, the Tehachapi Mountains on the east, and the southeast end of the fold belt on the west. This combined region, which is the most deformed part of the basin, has undergone significant late Cenozoic shortening through north-directed thrust faulting at the south margin, as well as extreme Neogene basin subsidence north of the thrust belt.

The sedimentary history of the San Joaquin basin, recorded in terms of unconformity-bounded depositional sequences, has been controlled principally by tectonism, but it has also been controlled by eustatic sea-level changes and, to a lesser degree, by climate. Plate tectonic events that had an influence on the basin include (1) subduction during the early Tertiary that changed from oblique to normal convergence in the later part of the Eocene, (2) the mid-Oligocene encounter of the Pacific-Farallon spreading ridge with the trench, and the consequent establishment of the San Andreas transform, (3) the northwestward migration of the Mendocino triple junction that induced extensional tectonism and volcanism in adjacent areas, and (4) the change in plate motions at 5 Ma that resulted in an increased component of compression normal to the San Andreas transform. Other tectonic events of a more regional scale that affected the San Joaquin basin include (1) clockwise rotation of the southernmost Sierra Nevada and tectonism that produced large en echelon folds in the southern Diablo Range, both perhaps related to Late Cretaceous and early Tertiary right slip on the proto-San Andreas fault, (2) uplift of the Stockton arch in the early Tertiary, (3) regional uplift of southern California in the Oligocene that was a precursor to the ridge-trench encounter, (4) extensional tectonism in the Basin and Range province, particularly in the Miocene, (5) wrench tectonism adjacent to the San Andreas fault in the Neogene, (6) northeastward emplacement of a wedge of the Franciscan Complex at the west side of the Sierran block and the associated deep-seated thrusting in the Cenozoic, and (7) the accelerated uplift of the Sierra Nevada beginning in the late Miocene.

The early Cenozoic sedimentary history of the San Joaquin basin differs from that of the later Cenozoic: the former is characterized by a few long-lasting basinwide depositional sequences, whereas the latter is characterized by shorter sequences of more local extent. This change in style of sedimentation took place during the Oligocene at about the beginning of the transition from a convergent continental margin to a transform margin. Paleogene basin history was controlled principally by subduction-related and proto-San Andreas fault-related tectonics and, to a lesser extent, the effects of changing eustatic sea level. A eustatic fall in sea-level was probably the principal cause for the regression recorded at the end of the upper Paleocene and lower Eocene depositional sequence, and it contributed to most other Paleogene regressions. Tectonic events related to the approach of the Pacific-Farallon spreading ridge became important in the Oligocene. Neogene basin history was controlled principally by the tectonic effects of the northwestward migration of the Mendocino triple junction along the California continental margin and by the subsequent wrench tectonism associated with the San Andreas fault system. Compression normal to the San Andreas in the latest Cenozoic, resulting from changes in relative plate motion, contributed to compressional deformation at the west side of the valley. Eustatic sea-level effects are less discernible in

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the Neogene, but a middle Miocene highstand probably contributed to the widespread transgression at that time. Climate was an important factor in basin history only in the latest Cenozoic (late Pliocene and Pleistocene), when alpine glaciers in the Sierra Nevada and a pluvial climate influenced sedimentation.

The San Joaquin basin, which at the end of the Mesozoic formed the southern part of an extensive forearc basin, evolved during the Cenozoic into today's hybrid intermontane basin. Its evolution comprises the gradual restriction of the marine basin through uplift and emergence of the northern part in the late Paleogene, closing off of the western outlets in the Neogene, and finally the sedimentary infilling in the latest Neogene and Quaternary.

INTRODUCTION

SETTING

The Great Valley of California, a 700-km-long by up to 100-km-wide alluvial plain between the Sierra Nevada on the east and the Coast Ranges on the west, is divided into the Sacramento Valley in the north and the larger San Joaquin Valley in the south. The south-flowing Sacramento River, draining the Sacramento Valley, and the north-flowing San Joaquin River, draining the northern part of the San Joaquin Valley, join in the Sacramento-San Joaquin Delta near Stockton (pl. 1, fig. 1); the delta in turn drains westward into San Francisco Bay. The Tulare Lake basin in the south-central San Joaquin Valley and the Buena Vista Lake basin at the extreme south end of the valley contain closed depressions, and both receive part of the drainage, at times, from the Kings and Kern Rivers.

Geologically, the San Joaquin Valley is an asymmetric structural trough with a broad, gently inclined, and little-deformed east flank and a relatively narrow west flank; the west flank is a steep homocline in the northern part of the valley, but becomes a belt of folds and faults in the southern part of the valley (pl. 1). The trough is filled with a prism of upper Mesozoic and Cenozoic sediments that reaches a thickness of over 9 km in the west-central part of the valley and at the south end. The sedimentary prism represents, in a broad sense, the fill of the San Joaquin sedimentary basin; however, this basin is, in a strict sense, a composite of a late Mesozoic and early Cenozoic forearc basin that was largely open to the Pacific Ocean on the west, and a later Cenozoic transform-margin basin. The basin-filling sediments rest on a westward-tilted block of crystalline basement composed of Sierra Nevada plutonic and metamorphic rocks under the eastern part of the valley and mafic and ultramafic rocks of a presumed ophiolite of Jurassic age under the central and western parts of the valley (Cady, 1975; Page, 1981). On the west side of the valley, the Mesozoic and early Tertiary Great Valley sequence, together with the conformably underlying ophiolite, is juxtaposed with the Franciscan Complex along a boundary fault termed the Coast Range thrust as first proposed by Bailey and others (1964). For many years, the Coast Range thrust was interpreted as a fossil subduction zone, but recent work based on seismic reflection and refraction suggests that the Franciscan has been thrust eastward as a wedge between crystalline basement below and the Great Valley sequence above (Wentworth and others, 1983; Wentworth and others, 1984) (pl. 1, sections *A*, *B*). The boundary between the Franciscan and the Great Valley sequence, then, becomes the roof thrust of the wedge and, unlike the hypothesized Coast Range thrust, extends no farther east than the tip of the wedge.

The Great Valley sedimentary basin is divided by the buried, transverse Stockton arch and Bakersfield arch. The Stockton arch, which is a broad structure that is bounded on the north by the Stockton fault (pl. 1) but has a poorly defined southern limit, separates the San Joaquin and Sacramento sedimentary basins. The Bakersfield arch separates the Maricopa-Tejon subbasin at the south end of the San Joaquin Valley from the remainder of the San Joaquin sedimentary basin. Neither arch has appreciable structural relief, but they did have an influence on sedimentation, as will be shown. The Tertiary depocenters of these basins are approximately coincident with the Pleistocene and Holocene Buena Vista and Kern Lakes basins in the south and the Tulare Lake basin in the central part of the valley. The Tehachapi-San Emigdio Mountains uplift that bounds the valley on the south might be considered a third transverse structure. Cenozoic strata in the San Joaquin Valley thicken southeastward from about 800 m over the western part of the Stockton arch to over 9,000 m in the Maricopa-Tejon subbasin in the south (pl. 1, section *D*). The Mesozoic and early Tertiary Great Valley sequence, on the other hand, thins southeastward and is apparently absent south of the Bakersfield arch.

PREVIOUS WORK

Although geological observations of rocks bordering the San Joaquin Valley date back to the late 1800's (Shedd, 1932), the valley itself received scant attention at that time. Geological study of the sedimentary deposits in the valley was spurred on in the early 1900's following the discovery of oil at the McKittrick (1887), Coalinga (1887), and Kern River (1901) oil fields. Knowledge of the geology of the valley accumulated as oil exploration progressed in the years preceding, and especially those following, World War II.

The first general review of the Cenozoic history of the valley was that of Hoots and others (1954), although Reed (1933) and Reed and Hollister (1936) touched on the San Joaquin Valley in their broader summaries of California and southern California geologic history, respectively. The Cenozoic history of the valley was updated by Repenning (1960) in a succinct, but stratigraphically comprehensive, summary and was further revised by Hackel (1966).

Bandy and Arnal (1969) applied a new technique—based on the analysis of benthic foraminiferal faunas from marine Tertiary rocks in the southern part of the valley—in an attempt to quantify basin subsidence and uplift. Foss' (1972) interpretation of the Tertiary marine stratigraphy emphasized the apparent synchroneity of depositional cycles on the east and the west sides of the valley, even though a different type of depositional sequence characterizes each area.

More recently, geologists have gone beyond describing the basin stratigraphy and history and have sought tectonic mechanisms that have controlled different aspects of basin evolution. Nilsen and Clarke (1975) discussed the tectonic setting for Paleogene sedimentation in the Great Valley together with other regions of California. Harding (1976) tied the structural evolution of the west-side fold belt to the history of movement on the San Andreas fault. Subsequently, others (notably Blake and others, 1978; Dickinson and Snyder, 1979; Howell and others, 1980) have related the origin of the San Joaquin basin, along with other California Neogene basins, to plate tectonic processes.

PURPOSE AND APPROACH

The theory of plate tectonics, since its emergence in the 1960's, has given a new perspective to the interpretation of regional tectonics (Blake and others, 1978; Howell and others, 1980; Page and Engebretsen, 1984). Concurrently, revisions in regional stratigraphy, resulting mostly from the application of recent improvements in global correlations and the work toward a standard global chronostratigraphic scale, allow more precise comparison of the timing of depositional events from widely separated parts of the San Joaquin basin. The goal of this report is to interpret the Cenozoic sedimentary record of the San Joaquin Valley in terms of external controls on sedimentation and to speculate, where possible, on the nature of the tectonic events responsible.

This report is chiefly a review of the Cenozoic geologic history of the San Joaquin basin in the light of current ideas on plate tectonics, regional tectonics, and eustatic sea-level change, although no exhaustive effort has been made to summarize all the extensive geological literature on the basin. It incorporates the results of several years of U.S. Geological Survey research by myself and others (notably D.E. Marchand, B.F. Atwater, J.W. Harden, and W.R. Lettis) on the San Joaquin Valley, the purpose of which was to elucidate the regional tectonic setting of the valley as background for more specific geologic hazards studies required in the siting, design, and construction of nuclear powerplants. A basin-study approach to understanding regional tectonic history was adopted. This assumes a basic cause and effect relation between tectonics and sedimentation, and also that the sedimentary fill in a basin is a record of tectonic activity.

GEOLOGY

Although the San Joaquin Valley, as the southern part of the Great Valley, constitutes part of a discrete geomorphic and structural province within the western Cordillera of North America, the geology is internally variable in both stratigraphy and style of deformation. Stratigraphically, the greatest variation is in the Neogene deposits, which comprise a thick section of marine sediments in the southern part of the basin but a relatively thin and entirely nonmarine section in the northern part. Structurally, the greatest differences are between the west-side fold belt and the little-deformed sedimentary cover of the Sierran block on the east side of the valley.

To facilitate description of the geology, the valley is subdivided into five regions on the basis of structural style (fig. 1, pl. 1). Although each region is structurally distinct in style of deformation and tectonic history, the boundaries between areas are necessarily arbitrary.

NORTHERN SIERRAN BLOCK

The northern Sierran block region of the San Joaquin Valley consists of the stable east limb of the valley syncline from the Stockton fault on the north to about the San Joaquin River on the south. The region, which is the least deformed part of the San Joaquin basin, includes as its dominant element the broad and poorly defined Stockton arch.

The Stockton arch is evident principally as an area where Paleogene and uppermost Cretaceous strata have been erosionally truncated (Hoots and others, 1954). There is little evidence of arching in overlying Tertiary units (Bartow, 1985) and no evidence of basement arching (Bartow, 1983) (pl. 1, section *D*). This structure probably formed initially in the latest Cretaceous or Paleocene, perhaps by local thickening of the Cretaceous section, and had a major period of uplift in the Oligocene. Its origin will be discussed further in the section "Regional Tectonics." The structure was a low-relief positive feature through most of the Paleogene.

The stratigraphy of the Modesto-Merced area is typical of that on the northeast side of the valley (pl. 2, col. 3); farther west, the stratigraphy is similar to that of the

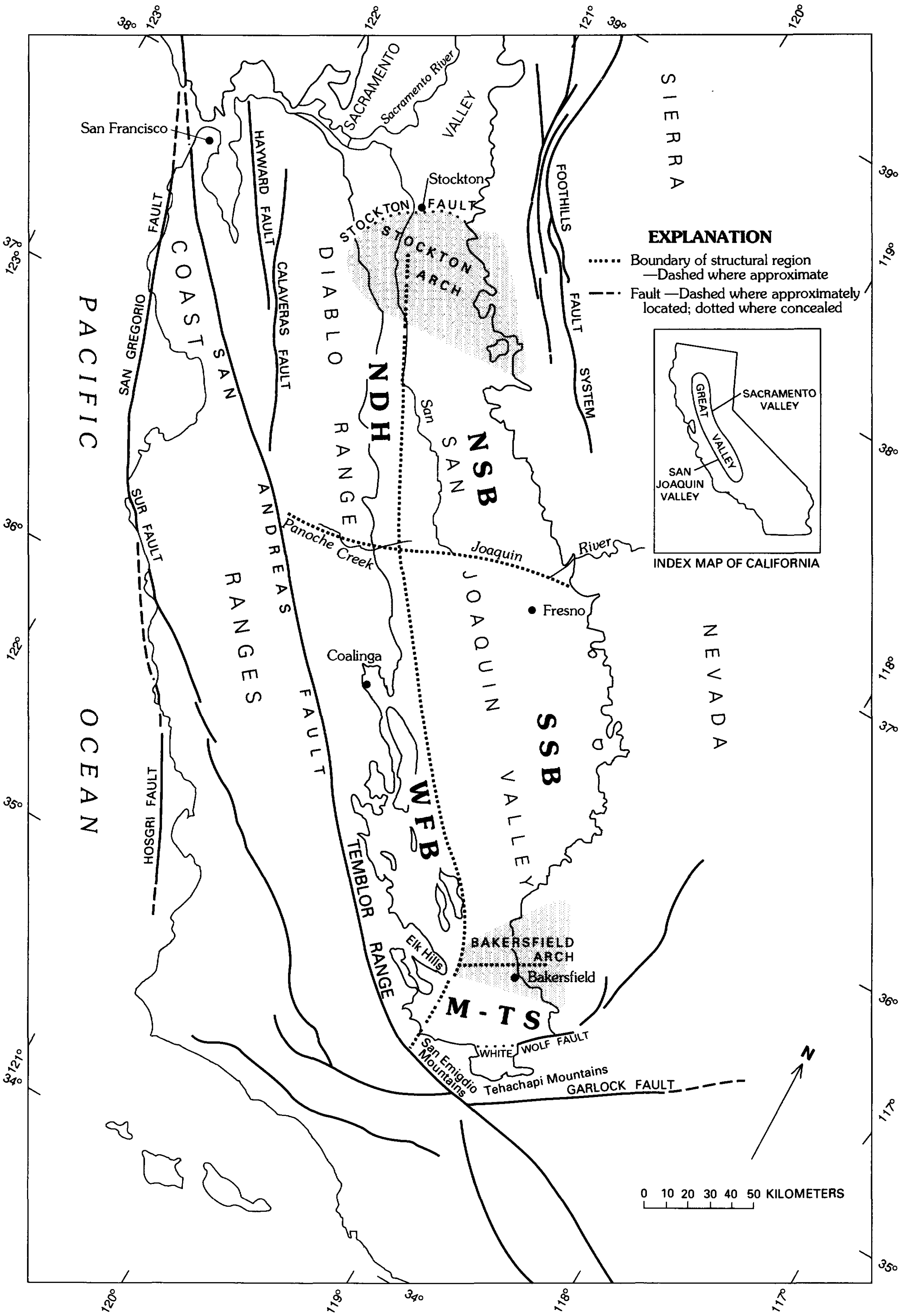

FIGURE 1.—Index map of central California showing the five structural regions of the San Joaquin Valley in relation to principal geographic and structural features. NSB, northern Sierran block; SSB, southern Sierran block; NDH, northern Diablo homocline; WFB, west-side fold belt; M-TS, Maricopa-Tejon subbasin and south-margin deformed belt.

Orestimba Creek area on the west side of the valley (pl. 2, col. 1). Over the Stockton arch (pl. 1), Paleogene strata are absent and nonmarine Neogene strata rest directly on the Great Valley sequence (Church and Krammes, 1958; Bartow, 1985). The Cenozoic deposits in this part of the valley are relatively thin (about 1,100 m) compared to the southern part of the valley, whereas the underlying Great Valley sequence is much thicker (over 3,000 m) (Hoffman, 1964) (pl. 1, section *A*).

Cenozoic deformation has consisted mostly of west or southwest tilting of the rigid Sierran block as evidenced by the subtle angular unconformities with discordances of generally less than 1° that separate the Cenozoic units along the northeast side of the valley (Grant and others, 1977; Marchand and Allwardt, 1981). Evidence of the earliest Cenozoic tilting, however, is provided by the truncation of Upper Cretaceous and Paleocene units by Eocene strata in the subsurface (Bartow, 1985). Discordance between Eocene and younger units is much less apparent than that between Eocene and pre-Eocene units, but there is some suggestion of tilting in the Oligocene, based on the differences in gradient of depositional surfaces in the Ione and Valley Springs Formations at the eastern edge of the valley (Marchand, 1977). These data are questionable, however, because a lack of traceable markers and erosional relief at the contacts makes it difficult to reliably determine gradients or dips in these units. Although there is little reliable evidence of Oligocene westward tilting, truncation of older units over the Stockton arch indicates uplift of that area, which, as the southern part of the basin continued to subside during the Oligocene, produced a southward tilt rather than a westward tilt. A hiatus representing most of the Oligocene is evidence that there was negligible subsidence in the western part of the block during that interval. In the Miocene section, there is little evidence of discordance between the Valley Springs and Mehrten Formations, although this evidence is again difficult to assess accurately. Later Neogene and Quaternary units, however, do show appreciable differences in gradient (Marchand, 1977; Marchand and Allwardt, 1981). It seems most probable that, while there may have been regional uplift or southward tilting of the northern Sierran block in the middle Tertiary, there was little southwest tilting until the late Miocene or Pliocene. Tilting continues to the present, probably at an accelerating rate.

Most of the Cenozoic faulting is localized along the Foothills fault system, consisting of the Bear Mountains and the Melones fault zones (pl. 1, fig. 1). This fault system originated as a major Mesozoic (pre-batholith) shear zone or suture and has been locally reactivated in the Cenozoic. Studies of the fault system by Woodward-Clyde Consultants for Pacific Gas and Electric Co.[1] revealed several locations where Cenozoic deposits are offset across the fault zones. Displacement at one locality on the Melones fault zone has been demonstrated to be younger than about 4 Ma (Bartow, 1980), and Quaternary movement is indicated elsewhere by shearing or offset of soils or Pleistocene colluvial deposits (Marchand, 1977; Schwartz and others, 1977). There is, however, no indication of present-day seismicity along these zones (Wong and Savage, 1983). Cenozoic normal faulting in the foothills belt, and elsewhere near the tectonic hinge line, was probably approximately coincident with the tilting; the faulting suggests that the west or valley side of the Sierran block was subsiding faster than the Sierra Nevada was rising, resulting in tensional faulting near the hinge.

Features possibly related to the Cenozoic normal faulting are the numerous northwest-trending lineaments in the eastern part of the valley (Marchand and Allwardt, 1978; Hodges, 1979). Most of these are probably not faults, but a few have 1 to 2 m of normal displacement of Pleistocene units (Marchand, 1977). Small normal faults with offsets of a few meters are present at a few localities in exposed Tertiary strata as well. There also appears to have been substantial displacements of the Eocene Ione Formation along a system of lineaments east of Merced (Marchand, 1977; Marchand and Allwardt, 1978), but detailed gravity profiles across one of the more prominent lineaments do not support significant offset of the basement surface. Data from one profile permit 2 m of fault offset of the basement surface within a few meters of the lineament; however, the interpretation of these gravity data is ambiguous because of uncertainties about erosional relief on the basement surface, lateral density variations in the basement, and density variations in overlying sediment (A. Griscom, written commun., 1978).

Few subsurface faults have been recognized in the northern part of the San Joaquin Valley; the largest of the known subsurface faults is the Stockton fault, which bounds the Stockton arch on the north (pl. 1). The Stockton fault is a south-dipping reverse fault that trends transversely to the regional structure. The fault, which appears to have a complex history, has a total down-to-the-north dip slip of as much as 1,100 m (Hoffman, 1964). It may have originated in the Late Cretaceous as a normal fault, or possibly a left-lateral strike-slip fault with a south-facing scarp (Teitsworth, 1964). It was reactivated as a reverse fault in the latest Cretaceous or Paleogene and was probably active through the early Miocene, although most of the down-to-the-north offset occurred during the Oligocene (Hoffman, 1964; Teitsworth, 1964; Bartow, 1985). In the Merced-Chowchilla area, another west-northwest-trending fault

[1]Unpublished report on geology of proposed Stanislaus nulear project by Woodward-Clyde Consultants for Pacific Gas and Electric Co., 1977.

is recognized mostly on the basis of apparent offset of the post-Eocene unconformity (Bartow, 1985). Its inferred trace appears to coincide with a diffuse surface lineament visible on satellite images (Antonnen and others, 1974; Hodges, 1979). The lineament, termed the Kings Canyon lineament, crosses the valley north of Chowchilla, parallels the south fork of the Kings River in the Sierra Nevada, and continues southeastward nearly to Death Valley. The ophiolite remnant at Del Puerto Creek and a major bend in the Ortigalita fault lie on the northwest projection of the lineament in the Diablo Range.

The reverse faulting on the Stockton fault, and the consequent elevation of Cretaceous rocks south of the fault to form the Stockton arch, indicates a general north-south compression from about the Paleocene through the early Miocene. Late Cenozoic southwest tilting of the Sierran block and subsidence of the west side, with concurrent normal faulting near the hinge, suggest east-west to northeast-southwest extension. The normal faulting, however, insofar as it represents flexural stress as the west side of the block subsided faster than the east side rose, is not necessarily evidence of regional extension. Present-day seismicity in the southern part of the northern Sierran block indicates north-south to northeast-southwest compression producing predominantly strike-slip and reverse faulting at depths greater than 12 km (Wong and Savage, 1983).

SOUTHERN SIERRAN BLOCK

The southern Sierran block comprises the southern part of the stable and little-deformed east limb of the valley syncline. Its south boundary is the crest of the Bakersfield arch, a broad southwest-plunging ridge of basement rock, and the north boundary is arbitrarily placed at the San Joaquin River (fig. 1, pl. 1). Both Cenozoic and Mesozoic sedimentary deposits thicken gradually southward and together total more than 5,000 m in the area south of Tulare Lake. Cenozoic strata alone reach a thickness of more than 4,500 m, whereas the Mesozoic rocks thin southeastward and pinch out or are truncated against the north flank of the arch (pl. 1, section *D*).

The stratigraphy of the Bakersfield arch area (pl. 2, col. 9) is typical of the southern part of this area. Outside the arch area, Tertiary rocks, particularly the older Tertiary, are not well known because of the absence of Tertiary outcrops between the San Joaquin River and the Tule River and because of the sparsity of deep wells. For much of the Neogene, the central part of the Southern Sierran block was a broadly fluctuating zone of transition between nonmarine deposition on the north and east and marine deposition on the south and west. The Cenozoic stratigraphy in the subsurface of the Hanford-Tulare area (pl. 2, col. 6) probably has some similarity to both the Bakersfield arch area to the south and the Kettleman Hills area to the west.

The San Joaquin Valley part of the southern Sierran block is structurally similar to the valley part of the northern Sierran block; differences are principally in degree of deformation rather than in style of deformation. The southwest-to-west tilt of the entire Sierran block increases southward so dips of exposed Tertiary units in the Bakersfield area average 4°–6°, in contrast to the 1°–2° dips in the north (pl. 1, sections *A*, *B*, *C*). Further indication of the increased tilt is provided by the greater height of the southern Sierra Nevada and the greater depth to basement in the southwestern part of the valley, although part of this difference in elevation is a result of normal faulting along the west edge of the southern Sierra Nevada.

Truncation of Cretaceous and Paleocene(?) strata indicates tilting prior to the middle Eocene of the southern as well as the northern Sierran block. Minor angular discordance between the Walker Formation or Vedder Sand and overlying Jewett Sand is evidence of tilting near the end of the Oligocene. An unconformity at the base of the "Santa Margarita" Formation that truncates older units, and a more extensive unconformity and truncation at the base of the Kern River Formation are evidence of the accelerating uplift and westward tilt of the southern Sierran block beginning in the late Miocene.

Normal faults along the east side of the valley are concentrated in the area of the Bakersfield arch. These faults generally trend northwest to north, although a secondary west to west-northwest trend is apparent (pl. 1). The net displacement is down to the southwest, although down-to-the-northeast faults are present (Bartow, 1984). One of the principal faults of this group is the Kern Gorge fault, along which basement rocks to the southwest have been downdropped more than 600 m. An important exception to the northwesterly fault trend is the Poso Creek fault that trends in a westerly direction through the Tertiary outcrop belt and then curves to the northwest to merge with the subsurface Pond fault.

Faulting appears to die out northwestward along the east edge of the valley, partly because Quaternary deposits overlap the Tertiary strata onto the basement rocks north of Deer Creek. Buried (or partially buried) faults that offset the basement rock surface have been inferred in the area between Porterville and Dinuba (Croft and Gordon, 1968) and near Clovis northeast of Fresno (Page and LeBlanc, 1969). The presence of these inferred faults is based principally on surface lineaments and a steeply west-sloping basement surface, but no fault offsets have been convincingly demonstrated. These faults are not included on plate 1.

Many subsurface faults have been inferred west of the Tertiary outcrop belt by others (Los Angeles Department of Water and Power, 1975, fig. 2.5.1–7A). Most of these faults seem to be small and have a predominant northwest trend; they have been recognized only where well density is sufficient for delineation of faults, that is, mainly in oil fields. No attempt has been made to generalize these on plate 1. The Pond fault and Greeley fault system are, however, major structures. The Pond fault, actually a zone of subparallel southwest-dipping normal faults up to 2 km wide, apparently joins the Poso Creek fault to the southeast (Los Angeles Department of Water and Power, 1975). Down-to-the-southwest offsets decrease upward from a maximum of over 500 m on the basement surface. Near the town of Pond, a zone of cracks extends to the ground surface, which has been downdropped as much as 23 cm across the fault (Holzer, 1980).

The buried Greeley fault system consists of an en echelon set of northwest-trending normal faults (pl. 1). The basement surface is downdropped on the northeast as much as 615 m, but offsets decrease upward so there is no apparent offset of strata younger than late Miocene (Los Angeles Department of Water and Power, 1975). The Greeley fault has been reported to have a large component of lateral displacement (Sullivan and Weddle, 1960). Webb (1977) inferred 670 m of right slip on the basis of apparent offset of Miocene channel sands, but he later reinterpreted (Webb, 1981) the apparent offsets as meanders in the channels. The Greeley fault system is paralleled on the southwest by a series of short low-amplitude folds that have their strongest expression in early Miocene and older strata. This folding could be (1) genetically related to strike-slip faulting, (2) due to compression that also would have produced reverse faulting, as is found on faults with similar trend farther west in the basin, or (3) a result of drape over a buried fault scarp. An intensive study of the Greeley fault system for a proposed nuclear powerplant site astride the northern segment of the fault, based on seismic-reflection profiles and oil well data (Los Angeles Department of Water and Power, 1975), concluded that the movement has been normal (down-to-the-east) and that there is no evidence of lateral displacement. This study apparently did not consider the possibility of reverse movement; however, the geometry of the Greeley structure, as seen on seismic-reflection sections, is sufficiently different from reverse fault structures like Semitropic anticline to seriously weaken the reverse fault hypothesis for the origin of the Greeley structure.

A large number of northwest-trending surface lineaments in the Kern River area were described by Warne (1955), who implied a relation to deep lateral faulting. More recent trenching of selected lineaments, however, shows no evidence of near-surface faulting (Los Angeles Department of Water and Power, 1975). The surface lineaments in the southeastern part of the valley are similar to those (described above) in the northeastern part of the valley. Their origin is unclear, but in neither case do they seem to be related to bedrock faults.

In contrast with the northern Sierran block where the normal faulting is mostly late Cenozoic in age, the faulting appears to be mostly Miocene or older in the southern part of the block. Although it is difficult to determine the time of inception of the normal faulting, subsurface evidence from both well sections (Bartow, 1984) and seismic sections (Los Angeles Department of Water and Power, 1975) indicates greater offset of the basement surface than of late Miocene or Pliocene horizons. Faults with a general north trend (northwest to north-northeast) and those, such as the Poso Creek fault, with a general west trend (west to west-northwest) seem to be similar in that offset decreases upward. In general, north-trending faults were active in the early Tertiary and again beginning in the late Miocene. West-trending faults may have had their origin in the latest Oligocene and early Miocene like those in the Maricopa-Tejon subbasin at the south end of the San Joaquin Valley, as will be shown in the section "Maricopa-Tejon Subbasin and South-Margin Deformed Belt," and were probably active until about the late Miocene. The Greeley fault, farther west and near the center of the valley, may have had its origin in the Cretaceous or earliest Tertiary and shows no offset of horizons younger than early Miocene (Los Angeles Department of Water and Power, 1975). Part of the movement of the normal faults in the southern Sierran block was, then, concurrent with the late Miocene to recent uplift of the Sierran block (pl. 2). However, a significant part of the offset was pre-uplift, and faulting seems to have ended in the Pliocene while uplift presumably continued. There are few faults on the north side of the Bakersfield arch that offset Quaternary deposits. The exceptions seem to be largely due to subsurface compaction as a result of fluid withdrawal—oil in the case of the Kern Front and Premier faults (Castle and others, 1983; Bartow, 1984) and ground water in the case of the Pond fault (Holzer, 1980). In addition to the normal faults involving basement rocks, a number of syndepositional growth faults formed during late Miocene sedimentation in the area west of Bakersfield (MacPherson, 1978).

North-trending normal faults of pre-Miocene age (including northwest-trending faults like the Greeley and Pond) indicate approximate east-west to northeast-southwest extension in the early Tertiary; these faults may be the only manifestation of a north-south regional compressive stress at that time, although there may be some possibility of minor right-lateral strike slip on northwest-trending faults like the Greeley fault. East-trending normal faults indicate north-south extension for the period during which they were active, probably about late Oligocene to late Miocene.

NORTHERN DIABLO HOMOCLINE

The northern Diablo homocline consists of the west limb of the valley syncline from the Stockton arch in the north to Panoche Creek in the south. It includes the northeast flank of the northern Diablo Range (fig. 1, pl. 1).

The stratigraphy of the Orestimba Creek area and the Los Banos-Oro Loma area (pl. 2, cols. 1 and 2) are representative of the Diablo homocline. Approximately 1,400 m of Cenozoic deposits in that area thin northwestward toward the Stockton arch, mostly through truncation of the marine older Tertiary units (Hoffman, 1964; Hackel, 1966; Bartow and others, 1985). Paleogene marine rocks, however, reappear in the Corral Hollow-Lone Tree Creek area southwest of Tracy. The present Diablo Range has resulted principally from Neogene tectonism, although there is some evidence that the northern Diablo Range existed as a positive area as far back as the Paleogene (Clarke and others, 1975; Nilsen and Clarke, 1975; Bartow and others, 1985). The relation between the Paleogene Diablo uplift and Stockton arch is unclear, but Neogene structures in the northern Diablo Range appear to be superimposed on the older positive areas.

The Cenozoic rocks of the northern Diablo Range form a northeast-dipping homocline in which the dips of the Tertiary strata generally range from 30° to 50° (pl. 1). Subordinate structures are principally faults, but folds are associated with the Vernalis and Black Butte faults near Tracy at the west end of the Stockton arch and a small anticline near Patterson produces a local reversal of dip in the homocline. Near Gustine, the dips of Tertiary strata flatten abruptly to 10° or less northeast of a northwest-trending fault.

Folding or tilting is mostly of Neogene age, although some deformation did take place in the Paleogene. The slight unconformity between the Great Valley sequence and overlying Paleogene units is evidence of mild deformation in earliest Tertiary time. Truncation of Paleogene units at the base of the Valley Springs Formation is apparent along the Diablo homocline, as it is elsewhere along the south side of the Stockton arch; this relation indicates post-Eocene uplift or tilting of the arch. Although the beginning of Neogene uplift of the Diablo Range is evidenced by the formation of coarse alluvial fan deposits derived from the range in the late middle to late Miocene (pl. 2), the angular unconformity at the base of the latest Pliocene and Pleistocene Tulare Formation marks the principal uplift of the range (Bartow, 1985).

The principal Cenozoic faults or fault zones of the northern Diablo homocline are (1) the Black Butte fault, a northwest-trending fault west of Tracy, (2) the Vernalis fault, a subsurface fault that parallels the Black Butte fault and trends at a right angle to the Stockton fault near its west end, (3) the Tesla-Ortigalita fault zone, the west boundary of the Diablo homocline and the present boundary between the Franciscan Complex and the Great Valley sequence, and (4) the San Joaquin fault zone, which lies along the west edge of the valley. The history of faulting is complex and, for some faults, not well understood. As with the folding, most Cenozoic faulting seems to be Neogene in age and it is difficult to identify specific structures as Paleogene in age because of the strong overprint of Neogene tectonism.

The Black Butte and Vernalis faults are subparallel, southwest-dipping reverse faults, each with an associated anticline on the upthrown side. The Black Butte fault involves units as young as the Tulare Formation and, therefore, must have been active as recently as the Pleistocene (Raymond, 1969). The age of the Vernalis fault is less well known because it is an entirely subsurface structure. Large offset at the base of the Valley Springs Formation (Bartow, 1985) suggests that most of the movement took place in the Miocene or later. Although the upper limit of faulting is not known and there is no evidence of Quaternary movement, the fault-plane solution for a 1977 magnitude 3.5 earthquake near Patterson approximately on-trend to the southeast indicates the same style of faulting as for the Black Butte fault (Wong and Ely, 1983).

The Tesla-Ortigalita fault is a zone of high-angle faults with a net down-to-the-east displacement that may total thousands of meters. The dip of the fault plane is not everywhere known, but it is locally a southwest-dipping reverse or thrust fault (Briggs, 1953). In the big bend segment of the Tesla-Ortigalita fault between Hospital and Del Puerto Creeks, the fault plane generally dips steeply in the direction of the downthrown block, which suggests that it is locally a normal fault (Maddock, 1964; Raymond, 1969). As Maddock pointed out, however, the fault may have been folded subsequent to its formation. Although movement on the fault zone has been predominantly dip slip, it is not known how much was in a reverse sense and how much might have been in a normal sense. The southern part of the zone from Quinto Creek to Little Panoche Valley shows evidence of right-lateral strike-slip displacement (Lettis, 1982; Anderson and others, 1982), and numerous fault-plane solutions for this part of the zone show chiefly right-lateral displacement (LaForge and Lee, 1982). The Holocene strike slip, however, may have been only recently superimposed on the predominant dip slip.

The history of the Tesla-Ortigalita fault zone is very poorly understood. What seems to be a nearly continuous fault zone may actually be an aggregate of fault segments having different origins and different histories. Some segments may have originated during Paleogene uplift, but most of the dip slip occurred in the Neogene. Similar elevations for an isolated 9-Ma basalt flow east of the fault zone near San Luis Reservoir and the base of the upper Miocene Quien Sabe volcanic field west of the fault zone led Lettis (1982, 1985) to conclude that there had been no appreciable differential vertical movement since the late Miocene. More recent work, however, suggests that the isolated flow was derived from a local vent in or near the fault zone itself and had no connection with the Quien Sabe Volcanics (D.H. Sorg, oral commun., 1986). The absence of vertical offset of Quaternary units across the southern segment of the fault zone indicates that there has been no appreciable Quaternary dip slip, but this segment does show evidence of late Cenozoic strike slip (Lettis, 1982; Anderson and others, 1982). The northern segment of the fault zone, the Tesla fault proper, juxtaposes upper Miocene deposits with the Franciscan and, therefore, must have had considerable post-late Miocene dip slip. The history of the big bend segment of the fault between Hospital and Del Puerto Creeks is much more difficult to assess. The present bend in the fault trace might be due to folding since the time of fault formation. If so, the timing of the folding is not known.

The San Joaquin fault zone is marked by a series of east-facing scarps and offset Quaternary depositional surfaces that were interpreted by Herd (1979b) as evidence of down-to-the-east normal faulting. Along much of the zone's length, however, the inferred faults are covered by upper Pleistocene and Holocene alluvium, so that there is some question about both the continuity and the dip of the faults. Bartow (1985) reinterpreted the zone as a series of reverse faults, a conclusion which seems more compatible with the regional framework. Available evidence, which shows that units as young as Pleistocene are offset, suggests that the San Joaquin fault zone may have been active at the same time as the Black Butte and Vernalis faults.

A set of subparallel faults between the Tesla-Ortigalita and the San Joaquin fault zones south of San Luis Reservoir (greatly generalized on pl. 1) was termed the O'Neill fault system by Lettis (1982, 1985). This fault system consists of numerous northeast-dipping faults that offset Quaternary pediment surfaces by as much as 100 m (Lettis, 1982, 1985). The faults are apparently bedding-plane slips in the underlying Great Valley sequence that formed in response to the strong bending of the upturned strata. These faults caused offsets of Quaternary erosion surfaces and their associated deposits that lie across the beveled edges of the Great Valley sequence.

One of the most fundamental structural features of the Diablo Range, as well as elsewhere in the Coast Ranges, is the contact between the Franciscan Complex and the Great Valley sequence (pl. 1, sections *A*, *B*). The original contact, although it has been greatly modified by younger faults like the Tesla-Ortigalita, is apparently tectonic (Page, 1981). This fault contact, commonly termed the Coast Range thrust, is interpreted as the roof thrust of a Franciscan wedge (Wentworth and others, 1983; Wentworth and others, 1984) that has had an influence on Cenozoic regional tectonics since, perhaps, as early as the Paleogene.

Paleogene deformation of the northern Diablo Range, which seems to have consisted mostly of broad regional uplift, implies northeast-southwest compression; however, the orientation of the stress cannot be determined with any certainty. Neogene structures reflect a general northeast-southwest compression, but latest Cenozoic right-lateral strike slip and seismicity on the southern segment of the Tesla-Ortigalita fault indicate a north-south or north-northeast–south-southwest compression producing a northwest-southeast shear, at least for the area between San Luis Reservoir and Panoche Valley.

WEST-SIDE FOLD BELT

The west-side fold belt extends along the southwest side of the valley syncline from about Panoche Creek on the north to the Elk Hills in the southwesternmost San Joaquin Valley. The belt includes the southern Diablo and Temblor Ranges and is characterized by Cenozoic folds and faults that trend, for the most part, slightly oblique to the San Andreas fault on the southwest (pl. 1).

The stratigraphy of the west-side fold belt is variable, as might be expected in a tectonically active area. Stratigraphic columns for four separate areas—the Vallecitos syncline, Kettleman Hills north dome, Lost Hills-Devils Den area, and Elk Hills area (pl. 2, cols. 4,5,7,8)—provide some indication of the variation. Total thickness for the combined Mesozoic and Cenozoic section may be over 9,500 m near the San Joaquin Valley syncline axis. As with the southern Sierran block part of the valley, there is a northward-thinning trend for the Cenozoic (pl. 1, sections *B*, *C*) and, particularly for the Neogene, a northward trend toward shallower marine and nonmarine facies. Middle Tertiary deposits representing some of the deepest water in the San Joaquin basin are found in the southern Temblor Range. Older rocks are not as well known in the southern part of the fold belt because of the absence of outcrops and the sparsity of wells that reached Paleogene strata.

The northernmost fold in the west-side fold belt is the Vallecitos syncline, located just south of Panoche Creek. The southeast boundary of the fold belt is arbitrarily placed east and south of Elk Hills where the fold trends change from northwest to west. The east boundary deviates from the valley syncline axis near Cantua Creek and south of Kettleman Hills to include the subdued Turk, Buttonwillow, Bowerbank, and Semitropic anticlines that, although lying east of the valley axis, are structurally more akin to the west-side fold belt than to the less-deformed southern Sierran block.

The intensity of deformation increases southeastward along the fold belt as well as southwestward across the belt toward the San Andreas fault (pl. 1). The increased intensity is evidenced by tighter folds and an increased number of reverse and thrust faults (Vedder, 1970; Dibblee, 1973a). Thrust faults seem to be predominantly west dipping, although the faulting in the interior of the Temblor Range is complex. Recent thrust-fault-generated earthquakes at the Coalinga anticline (May 1983) (Eaton, 1985b) and Kettleman Hills (August 1985) (Wentworth, 1985) are evidence of thrusting beneath major west-side folds and indicate the style of Holocene deformation along the east side of the fold belt (Wentworth and others, 1983; Wentworth and others, 1984; Namson and Davis, 1984; Medwedeff and Suppe, 1986). The west-side folds are, then, partly a reflection of deep-seated thrust deformation that is related to emplacement of a wedge of the Franciscan Complex.

Deflection of the shaleout line of the subsurface, lower Eocene Gatchell sand (of local usage) around the down-plunge end of the Coalinga anticline in the northern part of the fold belt provides evidence that the anticline probably formed in the Paleocene or early Eocene (Harding, 1976). Paleogene deformation is difficult to identify in the southern part, however, because of the deep burial of Paleogene rocks and the strong overprint of Neogene deformation. Harding (1976) outlined the Neogene development of the fold belt in relation to the history of strike slip on the San Andreas fault. The first en echelon folds in the Temblor Range or southern part of the fold belt date from the late early Miocene (near the Saucesian-Relizian boundary), whereas the easternmost anticlines in the fold belt (Buttonwillow, Bowerbank, and Semitropic) are entirely Pleistocene in age. The age of faulting in the fold belt is not well constrained, but eastward-verging thrust faults seem to have formed fairly late in the deformation history in the more tightly folded area near the San Andreas fault (Harding, 1976) and are still active at the west margin of the valley.

A fault along the southwest side of the Semitropic anticline has been interpreted as a normal fault (Los Angeles Department of Water and Power, 1975), but the asymmetry of the fold and its abrupt southeast boundary, as seen on proprietary seismic-reflection sections, suggest that it may be a northeast-dipping reverse fault. A structure interpreted as a reverse fault by Wentworth and others (1983) appears on a seismic-reflection section in a position on-trend with the Semitropic anticline fault to the northwest. The association of the fault at Semitropic with a fold is, in itself, suggestive of compressive deformation. The age of the fault is difficult to assess, but if it is genetically related to the fold, it would be Pliocene or Pleistocene in age. It may, however, be an older structure that has merely served to control the location of the younger fold.

The structures of the west-side fold belt cumulatively indicate north-south to northeast-southwest compression through the Cenozoic. During the early Paleogene and most of the Neogene, this compression was apparently manifested as a northwest-southeast shear couple. A tendency for Pliocene and Pleistocene structures to be oriented more parallel to the San Andreas fault indicates an increasing component of compression normal to the fault in the latest Cenozoic. Present-day seismicity at the San Joaquin Valley-Coast Ranges boundary in the northern part of the fold belt indicates continuing northeast-southwest compression (Eaton, 1985a).

MARICOPA-TEJON SUBBASIN AND SOUTH-MARGIN DEFORMED BELT

The Maricopa-Tejon subbasin and the south-margin deformed belt are structurally distinct areas, but they are probably genetically related. The Maricopa-Tejon subbasin is located at the extreme south end of the San Joaquin basin between the Bakersfield arch on the north and the deformed belt of the north flank of the San Emigdo Mountains on the south. These areas are bounded on the east by the Tehachapi Mountains of the southernmost Sierra Nevada and merge westward with the southeast end of the west-side fold belt (fig. 1, pl. 1).

The western part of the Maricopa-Tejon subbasin, the Maricopa subbasin proper, is characterized by its great depth—probably more than 9 km to basement in the central part. The south-margin deformed belt is characterized by the northward-directed thrust faulting at the south edge of the basin. Extreme Neogene subsidence, together with thrust faulting that resulted in several kilometers of crustal shortening in the late Cenozoic (Davis, 1983), is evidence that the south end of the San Joaquin basin is the most highly deformed part (pl. 1, section *D*).

The Maricopa subbasin contains the thickest Cenozoic deposits in the San Joaquin basin. Neogene and Quaternary strata are more than 6,100 m thick at the Paloma oil field, a few kilometers east of Buena Vista Lake Bed (pl. 1). The thickness of Paleogene strata in the central part of the basin is not known because few wells have reached the Paleogene and none have reached basement; however, more than 1,750 m of Paleogene strata crop out near San Emigdio Creek on the south side of the basin (pl. 2, col. 10) and a greater thickness might be present downdip to the north.

There are no known Cretaceous or Paleocene deposits south of the Bakersfield arch. Eocene strata rest on basement rocks in the San Emigdio Mountains and at South Coles Levee oil field at the west end of the Bakersfield arch (Church and Krammes, 1957), but no wells have reached the basement in the intervening area.

Paleobathymetries recorded in the middle Tertiary deposits of the Maricopa-Tejon subbasin are the deepest found in the San Joaquin basin. Abyssal depths (about 1,800 m) were reached in the Zemorrian, Saucesian and Luisian Stages (Bandy and Arnal, 1969). Paleogene nonmarine strata were deposited on the east and southeast, and the basin gradually shallowed through the late Neogene and became entirely nonmarine in latest Pliocene time.

Structural trends are variable in the Maricopa-Tejon subbasin and south-margin deformed belt, but there is a general west trend along the south margin of the basin. The northwest fold trends of the west-side fold belt change to west-northwest where that region merges with the deformed belt at the south end of the valley. The folds and faults of the San Emigdio Mountains, dominated by the Pleito thrust fault system, form a northward-directed salient with an average west fold trend. To the north and northeast, the northeast-trending White Wolf fault is the dominant structure. The White Wolf fault and the smaller Springs fault to the southeast both trend approximately parallel to the Garlock fault, which lies along the southeast side of the Tehachapi Mountains. Both faults, like the Garlock, show some geologic evidence of left-lateral movement. Farther northeast, the northwest- to west-trending Edison fault is an older Tertiary normal fault with down-to-the-north offset of over 1,500 m (Dibblee and Chesterman, 1953; Bartow, 1984).

The south margin of the San Joaquin basin, in addition to being the most highly deformed part of the basin, probably has the most complex tectonic history. Evidence of possibly the earliest deformation is provided by paleomagnetic data that indicate a clockwise rotation of the Tehachapi Mountains of 45° to 60° that took place between 80–100 Ma and 16 Ma (Kanter and McWilliams, 1982; McWilliams and Li, 1985). Some of this rotation probably occurred in the Late Cretaceous or early Tertiary and the remainder took place after eruption of volcanic rocks in the earliest Miocene (Plescia and Calderone, 1986). Geologic evidence of the earliest Cenozoic deformation is a major angular unconformity in the western San Emigdio Mountains where upper Oligocene and lower Miocene sediments of the Temblor Formation overlap truncated older Tertiary units and rest on basement rocks (Nilsen and others, 1973; Davis, 1986). Although no specific faults can be positively identified as having been active during the period of tectonism, which may have begun in the late Eocene and extended into the Oligocene, Davis (1986) suggested that Oligocene uplift of the San Emigdio Range was produced largely by a major south-verging thrust fault. The Caballo Canyon fault, identified by Davis (1986) as the Oligocene thrust, is an obscure fault (not shown on pl. 1) that has been subject to other interpretations (Davis, 1983), so the hypothesized Oligocene thrusting remains somewhat questionable.

Normal faults at the south margin of the basin have generally west trends (from northwest to northeast) and occur mainly in the subsurface (Hirst, 1986; Davis, 1986). These faults were active during the latest Oligocene and early Miocene, concurrent with volcanism dated at 22.1 to 22.9 Ma[2] (Turner, 1970) and basin subsidence (Hirst, 1986; Davis, 1986). The mostly west-trending Edison normal fault, as well as other normal faults of general west trend in this region of the basin, was also active at that time.

Most of the deformation of the San Emigdio Mountains, including uplift and folding, is late Cenozoic and is directly related to thrust faults of the Pleito fault system (Davis, 1986). These thrusts date only from the Pliocene and, on the basis of the earliest appearance of coarse detritus in the basin to the north, most of the uplift was in the late Pliocene and Pleistocene (Davis, 1986). Although the basin continued to subside through the Miocene, subsidence accelerated during the Pliocene (Davis, 1986; Hirst, 1986).

The White Wolf fault, which was the locus of the magnitude 7.2 Arvin-Tehachapi earthquake of July 1952, is a southeast-dipping reverse fault (Oakeshott, 1955; Stein and Thatcher, 1981). Total vertical separation on the basement surface has been at least 3,600 m (Stein and Thatcher, 1981) or possibly more than 4,600 m (Davis, 1983). Although seismologic data from the 1952 earthquake indicate a component of left-lateral slip (Oakeshott, 1955; Stein and Thatcher, 1981), evidence for large cumulative left-lateral displacement is ambiguous and the total lateral offset may be small relative to the large vertical offset (Davis, 1986).

The early history of the White Wolf fault is uncertain, but it may have originated as a down-to-the-northwest normal fault during the late Oligocene and early Miocene

[2]Dates have been converted from old to new (1977) constants according to Dalrymple (1979).

period of normal faulting (Davis, 1986). There is stratigraphic evidence of continued down-to-the-northwest movement accompanying basin subsidence through the Miocene, probably as a normal fault (Davis, 1986). More recently, probably during the Pliocene or Pleistocene, the configuration of the fault was apparently changed to the southeast-dipping reverse fault that it is today.

The stress regime in which the early Oligocene deformation took place is obscure, but it presumably involved an approximate north-south compression. The latest Oligocene and Miocene normal faulting and volcanism, in contrast, clearly indicates extension, probably with a general north-south orientation. The Pliocene to Holocene thrust faulting is also a clear indication of strong compressive tectonism, again with a north-south orientation. The tectonic history of the south end of the San Joaquin basin seems, therefore, to be one of alternating periods of compression and extension, all in a north-south direction.

MAJOR CONTROLS ON SEDIMENTATION

The Cenozoic stratigraphic record in the San Joaquin basin seems, at first glance, to be a far-from-ideal record of basin history. It is incomplete, particularly in the northern part of the basin; it is poorly dated in many places; and, it exhibits wide variations in facies from area to area. The gaps and complexity, however, are important parts of the record and they can provide important clues to basin history.

Stratigraphic sections from different parts of the basin (pl. 2) can be informally divided, where they consist mostly of marine deposits, into depositional sequences that are composed of transgressive-regressive couplets that formed principally in response to relative changes in sea level in combination with sedimentation. A relative rise in sea level, that is, the eustatic rise plus the effect of subsidence, does not necessarily equate with transgression, nor does a relative fall in sea level necessarily equate with regression. If, for example, sedimentation exceeds the relative rise of sea level, then a regression will result.

The marine sedimentary sequences of this report, which are commonly but not necessarily unconformity bounded, facilitate correlation from area to area within the basin. In a few cases an unconformity-bounded marine sequence may be approximately correlated with a nonmarine sequence on the basis of the bounding unconformities. The fact that correlatable sequences are present throughout the basin provides evidence for external control of the sedimentary record, and although the sequence is the primary record of basin history, the unconformities bounding the sequence are equally important. The goal in deciphering basin history is to identify the cause or causes of each event.

The major external controls on sedimentation are tectonism, eustatic sea-level change, and climate. The sedimentary record represents the complex interplay of all of these factors, although tectonism is clearly dominant. Any thick accumulation of sediments, such as that found in the southern San Joaquin basin, clearly implies tectonic subsidence. Furthermore, the location of this basin along an active continental margin virtually assures tectonic activity in some form, throughout the Cenozoic. The other factors, sea-level change and climate, play important roles as well, perhaps more so than previously recognized.

TECTONICS

Tectonics, as it applies to the Cenozoic San Joaquin basin, includes basin subsidence, uplift of the adjacent Sierra Nevada and Coast Ranges, and contemporaneous deformation of the basin itself such as faulting and folding. Closely associated with tectonism is volcanism at the margins of the basin and in adjacent regions.

The various aspects of Pacific Coast Cenozoic tectonics should be explicable in terms of the interactions of the crustal plates at the western edge of North America. Since the ascendency of the plate tectonics paradigm, knowledge of how plate interactions have influenced regional tectonics on the California margin has grown steadily. Before discussing the regional tectonic events that played a part in the evolution of the San Joaquin basin, it is appropriate to briefly review the plate tectonic events that are most relevant to the central California part of the continental margin.

PLATE TECTONICS

A subduction zone has existed at the western margin of North America throughout the Cenozoic (pl. 2). From the Late Cretaceous until about the middle or late Eocene (75 to 40 Ma), the relative plate motions resulted in oblique subduction of an oceanic plate, probably the Kula plate (Page and Engebretson, 1984). Rapid convergence rates during this period produced a low-angle subduction zone and consequent displacement of arc magmatism eastward from the Sierra Nevada into Colorado (Lipman and others, 1972; Snyder and others, 1976; Coney and Reynolds, 1977; Cross and Pilger, 1978). Oblique subduction at the central California margin continued until nearly the end of the Eocene when the Farallon plate, which had a more normal component of motion relative to North America, supplanted the Kula plate at central California latitudes (Page and Engebretson, 1984). Slowdown in the convergence rates from the late Eocene into the Oligocene resulted in steepening of the subduction zone and the consequent migration of volcanism southwestward from Idaho and Montana into Nevada (Lipman and others, 1972; Snyder and others, 1976; Cross and Pilger, 1978).

The San Andreas transform originated in mid-Oligocene time (28–30 Ma) (Atwater and Molnar, 1973; Engebretson and others, 1985) when the ancestral East Pacific rise first encountered the subduction zone. The term "San Andreas transform" is used here, as it was by Dickinson and Snyder (1979), for the whole system of subparallel faults that constitute the plate boundary. The initial slip was probably offshore on faults at or near the continental margin (Garfunkel, 1973; Dickinson and Snyder, 1979). Slip on the San Gregorio-Hosgri fault zone and San Andreas fault proper probably did not begin until nearly middle Miocene time (about 16–17 Ma); most of the initial slip was on the San Gregorio-Hosgri fault (Graham, 1978).

The transform lengthened as paired triple junctions migrated northwestward and southeastward along the continental margin. Relative positions of the North American and Pacific plates in the Neogene, reconstructed according to the global-circuit method (Atwater and Molnar, 1973), differ somewhat from the reconstruction by the hot-spot method (Engebretson and others, 1985). Although the difference between the two reconstructions is within the limits of probable error (Engebretson and others, 1985), the northward migration history of the Mendocino triple junction from the global-circuit method seems to provide the best fit to geologic history. The unstable configuration of the migrating triple junction (trench and transform not colinear) induced a wave of extensional tectonism in nearby regions (Dickinson and Snyder, 1979; Ingersoll, 1982). Local volcanism in west-central California was approximately coincident with the passage of the triple junction and is a further manifestation of the extensional regime (Dickinson and Snyder, 1979; Johnson and O'Neil, 1984; Fox and others, 1985).

The plate reconstructions of Atwater and Molnar (1973) suggest an increase in relative motion between the North American and Pacific plates at about 10 Ma, although this increase is expressed as a change in average rates for the period of 21 to 10 Ma versus 10 to 4.5 Ma and the change may have been a gradual one over several million years. Page and Engebretson (1984) showed an increase in slip rate at about 15 Ma, and Cox and Engebretson (1985) inferred a small change in motion at 8.5 Ma, but nothing at 10 Ma. The differences may be more apparent than real and may be simply a result of the different methods used in the reconstructions. In any case, there was an acceleration of the slip rate on the San Andreas fault at 10 to 12 Ma (Huffman, 1972; Graham, 1978).

At about 5 Ma the motion of the Pacific plate changed to a more northerly direction, resulting in a component of compression normal to the San Andreas transform (Minster and Jordan, 1984; Page and Engebretson, 1984; Cox and Engebretson, 1985). Opening of the Gulf of California at about the same time, 5.5 Ma according to Moore and Curray (1982), indicates increased coupling between the sliver of former continental terrane west of the transform and the Pacific plate. This increased coupling resulted in an acceleration of the slip rate on the San Andreas fault.

REGIONAL TECTONICS

The earliest Cenozoic tectonic events that affected the region of the San Joaquin basin were probably related to movements of the proto-San Andreas fault during the Paleocene and possibly early Eocene. Right-lateral strike-slip movement on the proto-San Andreas was concurrent with oblique subduction and is generally believed to have ended by about the end of the Paleocene (Nilsen and Clarke, 1975; Dickinson and others, 1979). Inasmuch as oblique subduction at the central California margin continued until nearly the end of the Eocene, strike-slip movement could conceivably have continued well into the Eocene, although the evidence is equivocal. A clockwise rotation of the southernmost Sierra Nevada, demonstrated by paleomagnetic data, has been inferred to reflect oroclinal bending due to right-lateral shear along the proto-San Andreas fault (Kanter and McWilliams, 1982; McWilliams and Li, 1985). This orocline might also be considered a tectonic effect of the accretion of the Tujunga terrane (part of the Salinia composite terrane) to the North American craton in the Mojave region near the end of the Paleocene (Howell and others, 1987; Nilsen, 1987). The large folds at the northwest end of the fold belt—that is, the Vallecitos syncline, Joaquin Ridge anticline, and White Creek syncline—are apparently of the right age and orientation to have originated as an en echelon fold set associated with right slip on the proto-San Andreas fault (Harding, 1976). Early Paleogene fold growth might also be considered an indication of thrusting associated with early eastward movement of a Franciscan wedge at depth. The evidence is insufficient to make a definitive statement, but both processes may have been operative.

The Stockton arch at the north end of the San Joaquin basin has a more enigmatic origin. It has been suggested that it formed by crustal buckling at the tectonic transition between a region of oblique subduction with proto-San Andreas strike slip to the south, and a region of oblique subduction without strike slip to the north (Nilsen and Clarke, 1975; Dickinson and others, 1979).

This origin is unlikely because of the absence of basement arching (pl. 1, section *D*). The broad high of Cretaceous rocks made apparent by later truncations is probably a result of localized structural or sedimentary thickening of the Cretaceous section. Structural thickening, although possible, seems less likely because there is no evidence of stratigraphic repetition by thrust faults or any other deformation within the Cretaceous section. Sedimentary thickening, on the other hand, seems more likely because there is some evidence of thickness changes associated with the arch. An isopach map of the Lathrop sand (of local usage), for example, shows an abrupt northward thinning across the trend of the Stockton fault (Hoffman, 1964). The total Cretaceous section is also thicker south of the fault, even though some of the section has been removed by post-Eocene erosion (pl. 1, section *D*). Well data indicate that the basement is higher north of the Stockton fault than it is to the south, under the arch (Hoffman, 1964; Teitsworth, 1964; Bartow, 1983), and thickness changes within the Cretaceous section imply down-to-the-south faulting concurrent with sedimentation. Inasmuch as Cenozoic movement on the fault has been down to the north, there must have been a major south-side-down offset of the basement surface during the Cretaceous. The high basement on the north and the increased Cretaceous thickness on the south can be alternatively attributed to post-Cretaceous left-lateral slip on the Stockton fault, but the amount of offset required (several kilometers) makes this an unlikely interpretation. Latest Cretaceous or Paleocene south-side-up movement on the Stockton fault would reduce the Cretaceous throw on the basement surface and raise the Cretaceous rocks in the area to the south. The feature that has come to be known as the Stockton arch might be, then, simply an up-tilted fault block. Whatever its origin, the Stockton arch area persisted as a positive element throughout the remainder of the Cenozoic.

The Franciscan-Great Valley sequence fault boundary (the Coast Range thrust) may have been reactivated in the Tertiary, initially during the period from about 60 to 50 Ma when plate convergence was at a maximum (Page and Engebretson, 1984). Cenozoic activity at this boundary probably resulted from the emplacement of a wedge of Franciscan between the Great Valley sequence above and crystalline basement below, as proposed by Wentworth and others (1984) (pl. 1, sections *A*, *B*).

Oligocene events in southern California had an effect on the southernmost San Joaquin basin. A regional uplift in the south, together with the formation of fault-bounded alluvial basins, has been ascribed to the approach of the ancestral East Pacific rise to the North American plate and subduction of young, buoyant lithosphere somewhat in advance of the actual arrival of the spreading ridge at the trench in mid-Oligocene time (Nilsen, 1984; Crowell, 1987). The principal effect for the San Joaquin basin seems to have been uplift and faulting of the south end of the basin, particularly the San Emigdio Mountains and southernmost Sierra Nevada (Davis, 1983, 1986).

The evolution of extensional deformation in the Basin and Range province probably also had an indirect effect on the San Joaquin basin. The beginning of the extensional stress regime in the Basin and Range during the Oligocene is related to the evolution of the arc-trench system. The transition from compression to intra-arc extension and then to back-arc extension took place as the subduction angle steepened and the eastern limit of magmatism consequently migrated southwestward (Eaton, 1979). The intra-arc and back-arc extension was oriented at right angles to the trend of the trench (Zoback and others, 1981) and may have produced compression in the region (including the San Joquin basin) between the Basin and Range province and the trench.

Wrench tectonics in conjunction with deep-seated thrusting along the southwest side of the basin adjacent to the San Andreas fault dominated the Neogene. The earliest conclusive evidence of en echelon folding appears in the stratigraphic record near the end of Saucesian time (about 16–17 Ma) (Harding, 1976). Additionally, the provenance and distribution of Miocene sandstone in the Temblor Range suggest that strike slip may have begun by late early Miocene time on the central California portion of the San Andreas fault (Graham and others, 1986). This timing is consistent with the fault offset history of Huffman (1972, fig. 13). Progressive basinward expansion of the fold belt, together with cessation of folding near the San Andreas while it continued farther east, suggested to Harding (1976) that the folds and the San Andreas fault were independent responses to a diffuse coupling in the deep crust, and that the folds propagated outward in an expanding deformational front. The fact that younger folds, like the Kettleman Hills and Lost Hills anticlines, are approximately parallel to the San Andreas and not oblique to it indicates that they are not purely a response to shear in the San Andreas system. The basinward expansion of the Kettleman Hills-Lost Hills part of the fold belt seems to be, in contrast to the model proposed by Harding (1976), a response to an eastward-advancing thrust front at depth associated with the emplacement of a Franciscan wedge at the base of the Great Valley sequence (Wentworth and others, 1983) (pl. 1, sections *A*, *B*).

Extension in the Basin and Range province again had an effect on the San Joaquin basin in the Miocene. Basin and Range faulting began in the late Miocene, probably about 10 Ma (Zoback and others, 1981), and probably related left-lateral movement on the Garlock fault is assumed to have begun at about the same time. This extension resulted in the westward movement of the Sierra Nevada block, carrying the San Joaquin basin with it, and the consequent formation of the bend in the San Andreas fault (Davis and Burchfiel, 1973; Hill, 1982; Bohannon and Howell, 1982). The space problem arising from this westward movement probably caused compression normal to the San Andreas at the west side of the Sierran block (Wentworth and Zoback, 1986).

The last major uplift of the Sierra Nevada is also believed to have begun after 10 Ma (Christensen, 1966; Huber, 1981), but the uplift and the westward movement may not have been directly related. It has been suggested that the late Cenozoic uplift of the Sierra Nevada was caused by thermal thinning of the lithosphere after northward passage of the Mendocino triple junction (Crough and Thompson, 1977; Mavko and Thompson, 1983). The cold subducting slab north of the triple junction insulated the overlying continental lithosphere, whereas subduction had stopped south of the triple junction which allowed the base of lithosphere to be heated and converted to less-dense asthenosphere.

Acceleration in the slip rate on the San Andreas fault in latest Miocene and Pliocene time correlates with an increase in deformation in the fold belt adjacent to the fault (Harding, 1976); this acceleration may have contributed to the rapid subsidence of the southern San Joaquin basin (Dickinson and Snyder, 1979; Davis, 1983). Fault-normal compression in Pliocene and Pleistocene time, resulting from changes in relative plate motion at about 5 Ma, produced fault-parallel folds and reverse faults (Zoback and others, 1987). This compression probably caused uplift of the Temblor and Diablo Ranges (Engebretson and others, 1985) and, together with the developing bend in the fault, was probably the principal factor leading to northward-directed thrusting at the south end of the basin.

The Cenozoic subsidence history of the San Joaquin basin in relation to regional tectonics is not well known. Inferences about subsidence have been made from estimates of paleobathymetry and from the present depth and basinward-thickening trends of individual stratigraphic units, but because of the lack of precision in both paleoecology and absolute age of the commonly used benthic foraminiferal faunas, some margin of error exists in reconstructions of subsidence history. Preliminary attempts at geohistory analysis have been made by Dickinson and others (1987), Moxon (1986), and Olson and others (1986). Collectively, these studies suggest periods of rapid subsidence in the (1) late Paleocene and earliest Eocene, (2) middle Eocene, (3) latest Oligocene and early Miocene, and (4) middle and late Miocene. Uplifts are suggested in the Oligocene and near the early Miocene-middle Miocene boundary. These generalizations are based on preliminary geohistory analyses of widely separated parts of the basin and, consequently, an event identified from any one locality is not necessarily a basinwide event. It should be noted that a rapid rise in relative sea level can also result from steady basin subsidence in combination with a eustatic rise in sea level. Nevertheless, geohistory analysis is a promising technique and will ultimately provide valuable information on basin evolution. At the present time, however, a detailed subsidence history has not been established for the San Joaquin basin, nor is it possible to identify with much certainty the specific causes of tectonic subsidence.

SEA-LEVEL CHANGE

Eustatic sea-level change can result from changes in the volume of ocean water, changes in the volume of the ocean basin, or possibly both. The processes that can contribute to sea-level change were reviewed by Pittman (1978) and Donovan and Jones (1979). Those that are potentially most significant in terms of rate and magnitude are (1) fluctuations in continental ice sheets, (2) changes in volume of the mid-ocean ridge system, and (3) desiccation and flooding of isolated ocean basins. An additional process, suggested by Schlanger and others (1981), is mid-plate thermal uplift and volcanism in ocean basins. Ultimately, all processes affecting sea level can be traced back, directly or indirectly, to global tectonics (fig. 2).

Sea-level change controls sedimentation by controlling the environment of deposition. This is most obvious near the strandline where change in sea level produces lateral shifts of nonmarine and shallow-marine environments. The stratigraphic record of sea-level change along an active continental margin will probably be obscure because the effects of the prevailing tectonism will tend to mask the relatively minor effects of sea-level change. Without a global standard sea-level curve to which local sections may be compared, it would be virtually impossible to identify any particular event in the sedimentary record as sea-level controlled. The coastal-onlap curves of Vail and coworkers (Vail and others, 1977; Vail and Hardenbol, 1979) and the eustatic sea-level curve of Haq and others (1987) provide a standard for comparison. The eustatic sea-level curve (Haq and others, 1987) used in this report (pl. 2) has been adjusted to fit the Cenozoic chronology of Berggren and others (1985). Although the basic concept of eustatic fluctuation of sea level through geologic time is generally accepted, questions have been raised about the actual influence of sea level on the stratigraphic record and about the validity of the Vail sea-level model (Watts, 1982; Parkinson and Summerhayes, 1985; Miall, 1986). The Vail model is still being tested and revised, but some results to date suggest that it may be accurate enough, if used with caution, to serve as a useful tool in interpreting continental margin history (May and others, 1984; Poag, 1984; Poag and Schlee, 1984; Aubry, 1985; Poag and Ward, 1987).

The coastal-onlap curve of Vail and others (1977) was originally equated directly with relative change of sea level. The asymmetric shape of the curve, representing long periods of sea-level rise followed by apparently instantaneous fall, provoked some controversy. It is now recognized that the coastal-onlap curve does not equate directly with global change in sea level, but the lows in the sawtooth pattern, representing downward shifts of coastal onlap, mark times of global unconformities. These unconformities correlate with inflection points on the eustatic sea-level curve during periods of falling sea level, so that the lowstand of sea level actually comes shortly after the downward shift in coastal onlap (Vail and others, 1984). Unconformity-bounded sequences of local sections can then be compared with the eustatic curve by correlating unconformities with the inflection points on the curve. Correlation of unconformities between the global standard and local sections is evidence that supports sea-level control, but it does not prove exclusive sea-level control because global tectonism can affect sea level as well as local tectonic activity.

CLIMATE

With the exception of glacial and periglacial environments of the Ice Ages, climate is the least influential of the controls on sedimentation. The climatic influence is more likely to be reflected in the character of the sediments, that is, facies or mineral composition, than it is in the control of transgressions or regressions.

The Tertiary was a period of general climatic deterioration from the very warm global climates of the Late Cretaceous to the cool glacial climate of the Quaternary. Climates were warmest during the Eocene, when a low latitudinal temperature gradient and high precipitation prevailed (Frakes, 1979; Wolfe, 1978). A rapid deterioration near the Eocene-Oligocene boundary led to glacial conditions in Antarctica during the Oligocene (Frakes, 1979; Mathews, 1984) and generally cooler, dryer global climates. Temperatures warmed somewhat during the late Oligocene, early to middle Miocene, and latest Miocene, but at no time were temperatures as warm as those of the Eocene (Wolfe and Hopkins, 1967; Addicott, 1970). The climate fluctuated in the Neogene, but the overall trend was toward cooler temperatures. Sea-level glaciation in the Arctic and alpine glaciation in the Sierra Nevada both date from the late Pliocene (Frakes, 1979).

In the San Joaquin basin, the warm, wet tropical climate of the Eocene is reflected in the quartz-kaolinite sandstone and lignite, along with the associated laterites, of the Eocene deposits. Outwash from alpine glaciers in the Sierra Nevada contributed to the San Joaquin basin alluvial sedimentation beginning in late Pliocene time; the pluvial climate of the Pleistocene resulted in a series of large lakes in the San Joaquin Valley.

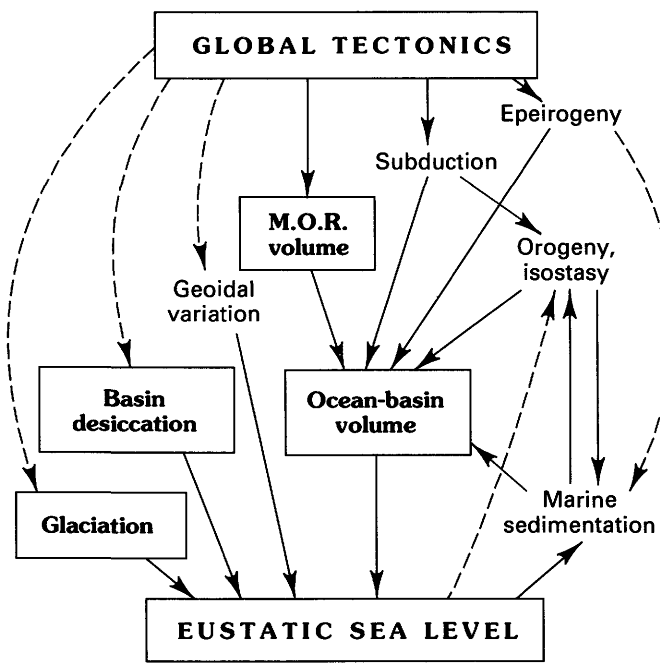

FIGURE 2.—Interrelation of factors causing eustatic fluctuations of sea level. The major controls on volume changes of the ocean basins and of the global hydrosphere are enclosed in boxes. Ultimately, global tectonics is the overriding influence, either directly (solid lines) or indirectly (dashed lines). M.O.R., mid-ocean ridge. From May and others (1984).

THE SEDIMENTARY RECORD

The early Cenozoic sedimentary history of the San Joaquin basin is fundamentally different from that of the later Cenozoic, as can be seen on plate 2. The early Cenozoic is characterized by a few long-lasting basinwide depositional sequences, whereas the later Cenozoic is characterized by shorter sequences of more local extent. The change took place during the Oligocene at about the beginning of the transition from a convergent continental margin to a transform margin. This fundamental change in sedimentation patterns seems to show a clear correlation to the change in continental margin tectonics, but other more localized sedimentary events are not always easily analyzed.

PALEOGENE

GREAT VALLEY SEQUENCE

The Upper Cretaceous and lower Tertiary part of the Great Valley sequence represents the last phase of deposition in the late Mesozoic to early Tertiary forearc basin. It consists principally of deep-sea fan deposits and associated facies on the west side of the basin and shallow-marine to deltaic deposits on the east side (Ingersoll, 1979; Cherven, 1983). The uppermost or lower Tertiary part of the sequence consists mostly of westward-prograding slope, shelf, and deltaic facies (Cherven, 1983). The Great Valley sequence is apparently absent south of the Bakersfield arch, as noted earlier. This absence may be due to uplift associated with the oroclinal bending of the southernmost Sierra Nevada in the early Tertiary.

The Great Valley sequence is separated from the overlying upper Paleocene and lower Eocene sequence, consisting principally of the Tesla and Lodo Formations, by an unconformity (pl. 2). In the northern Diablo Range at the west end of the Stockton arch, there is a slight angular discordance at the unconformity, whereas farther south on the west flank of the northern Diablo Range, the Moreno and Tesla Formations are concordant. The contact between the Moreno and Laguna Seca Formations appears to be gradational in exposures just south of Los Banos (Briggs, 1953), but still farther south at the type area of the Lodo Formation, there is paleontologic evidence of a hiatus (Berggren and Aubert, 1983); in the Vallecitos syncline there is evidence of an unconformity with westward overlap of the Lodo Formation on the Great Valley sequence (White, 1940; Dibblee, 1979a). Despite apparent conformity locally, there is probably at least a disconformity at the contact throughout the basin, and the base of the overlying sequence is transgressive.

An angular unconformity at the top of the Great Valley sequence was probably produced in the northern part of the basin by uplift of the Stockton arch during the Paleocene. In the central and possibly southern Diablo Range, the unconformity was probably a result of either concurrent en echelon folding associated with movement on the proto-San Andreas fault (Harding, 1976) or thrusting associated with emplacement of a Franciscan wedge. The angular discordance is always slight or nonexistent, however, and indicates only mild deformation.

The unconformity between the Great Valley sequence and the upper Paleocene and lower Eocene sequence correlates with the boundary between global supercycles "TA1" and "TA2" in the sequence stratigraphy of Haq and others (1987) (pl. 2). The good correlation suggests that sea-level change was a major contributing factor to the regression that produced the unconformity. The widespread nature of the unconformity in the San Joaquin basin and the absence of evidence for strong deformation also support this interpretation.

UPPER PALEOCENE AND LOWER EOCENE SEQUENCE

The deposits of the upper Paleocene and lower Eocene sequence show a prominent shoaling trend northward onto the Stockton arch (Nilsen and Clarke, 1975). The Lodo Formation in the Vallecitos syncline area, and to the southeast, consists of thin neritic deposits at the base that are overlain by middle or lower bathyal deposits (Berggren and Aubert, 1983). In the northern part of the basin, the equivalent units consist of neritic or shallower facies that include common nearshore marine and fluvial-deltaic facies flanking the Stockton arch (Dickinson and others, 1979). The amount of deepening during this rapid transgression in the southern part of the basin was 400 m or more (Berggren and Aubert, 1983). This is more than could be accounted for by a sea-level rise alone and indicates a pronounced southward or southeastward tilt of the basin during latest Paleocene or early Eocene time.

Deposition of the upper Paleocene and lower Eocene sequence ended after a regression that culminated in a widespread unconformity (pl. 2). The overlying Eocene sequence, consisting of the Domengine Sandstone, the Kreyenhagen Shale, and their correlatives, rests on rocks as old as Cretaceous in the southern Diablo and northern Temblor Ranges (Dibblee, 1973a) and laps onto Sierran basement rocks on the east side of the basin (Bartow, 1985). Although the sequence is not in depositional contact with Franciscan rocks, Franciscan detritus, in the form of red and green radiolarian chert pebbles or glaucophane, is present in basal sandstones of the sequence in the southern Diablo Range (Nilsen and Clarke, 1975; Dickinson and others, 1979). The unconformity seems to be present throughout the northern part of the basin, as evidenced by the local truncation of lower Eocene and even Paleocene rocks (Church and Krammes, 1958; Bartow, 1985). However, from the Kettleman Hills southeastward, the upper Paleocene and lower Eocene and the overlying Eocene sequences appear to be conformable (Church and Krammes, 1959). There are virtually no data on rocks older than late Eocene in the southern Temblor Range. The offset equivalent of these older rocks on the opposite side of the San Andreas fault, however, now lies in the Santa Cruz Mountains more than 300 km to the northwest (Clarke and Nilsen, 1973). The deep-sea fan deposits of the offset Point of Rocks Sandstone Member of the Kreyenhagen Shale (San Joaquin basin) and Butano Formation (Santa Cruz Mountains) span the time represented by the regression, but indicate continued bathyal sedimentation in the southwestern part of the basin (Clarke, 1973; Nilsen and Clarke, 1975) and in its western extension (Nilsen and Clarke, 1975; Stanley, 1985).

The unconformity between the upper Paleocene and lower Eocene sequence and the overlying Eocene sequence correlates with the boundary between the "TA2" and "TA3" global supercycles of Haq and others (1987) (pl. 2). Similarly correlative unconformities have been recorded in several areas on the Pacific coast (Berggren and Aubert, 1983; May and others, 1984), in Libya (Barr and Berggren, 1981), and in several areas of Europe (Aubry, 1985). The global nature of this unconformity is strong evidence for lowered sea level at the end of the early Eocene. However, an angular discordance at the unconformity and Franciscan detritus above the unconformity provide convincing evidence of concurrent tectonic activity in central California. Coarse Franciscan detritus appears to be concentrated in a belt that lies in the southern Diablo Range as far north as the Vallecitos syncline. Assuming 305 km of Neogene offset on the San Andreas fault (Clarke and Nilsen, 1973) and 115 km on the San Gregorio-Hosgri fault trend (Graham and Dickinson, 1978), the belt would lie adjacent to the inferred Paleogene position of the north end of the Salinia terrane. If 150 km of offset is assumed for the San Gregorio-Hosgri fault (Clark and others, 1984), the belt would lie just north of the inferred north end of the Salinia terrane. This location of the belt suggests a relation between uplift of the Franciscan Complex and emplacement of the Salinia terrane. Franciscan source areas may have been uplifted following emplacement of the Salinia terrane to the west, as suggested by Dickinson and others (1979). Inasmuch as emplacement of the Salinia terrane opposite the southern San Joaquin basin in the early Tertiary must have involved strike slip on the proto-San Andreas or closely related faults, the uplift in the area of the Diablo Range may, then, have been due to related wrench tectonism that continued into the early Eocene. The role of wrench tectonism at that time is, however, questionable, and the uplift might better be considered as evidence of early Tertiary thrust emplacement of a Franciscan wedge at depth under the southern Diablo Range, just north of the north end of the Salinia terrane. Whatever the tectonic mechanism, the regression at the end of the early Eocene was probably produced by a combination of eustatic sea-level change and local uplift.

EOCENE SEQUENCE

Deposition of the Eocene sequence began during a rapid transgression. A minor hiatus near the base of the sequence (Milam, 1985) is associated with a condensed section, as evidenced by abundant glauconite and low sedimentation rates in the basal Kreyenhagen Shale. Milam (1985) calculated a sedimentation rate of less than 1 cm/1,000 years for the lower part of the Kreyenhagen. The hiatus and condensed section are results of rapid rise of relative sea level that produced starved-basin-type sedimentation and was probably caused by rising global sea level combined with basin subsidence. Deposition of the bathyal shale that makes up most of the sequence corresponds to a highstand of sea level on the eustatic sea-level curve of Haq and others (1987).

A regression at the end of the Eocene is apparent mostly on the flanks of the Stockton arch in the northern part of the basin and in the San Emigdio Mountains at the south end of the basin (pl. 2). A minor reversal of the overall Paleogene transgressive trend along the southeastern margin of the basin is evidenced by intertonguing nonmarine and shallow-marine deposits (Bartow and McDougall, 1984). Elsewhere in the southern part of the basin, deep-marine sedimentation prevailed into the Oligocene with only slight to moderate shallowing; an unconformity in the Temblor Range area (pre-Temblor Formation) was interpreted by Carter (1985) as a result of submarine erosion at bathyal depths. Evidence of tectonic activity near the Eocene-Oligocene boundary appears in the Poverty Flat Sandstone along the east flank of the Diablo Range in the northwest, and in the Tecuya and Pleito Formations in the south. The Poverty Flat contains a conglomerate that consists principally of red radiolarian-chert pebbles derived from the Franciscan Complex and a few other pebbles of Franciscan and ophiolite lithologies (Bartow and others, 1985). This conglomerate represents the earliest appearance of appreciable coarse Franciscan detritus in the northern Diablo Range. Lenses of granitic breccia at the base of the Tecuya (Nilsen and others, 1973) and in the lower part of the Pleito in the San Emigdio Mountains were interpreted by DeCelles (1986) as a result of a seismically triggered rockslide and associated submarine mass movements. Syndepositional deformation structures in coeval sediments were ascribed to the results of seismic shaking. This inferred seismic event may mark the beginning of Oligocene tectonic activity at the south end of the basin.

Uplift of a Franciscan source area in the northern Diablo Range at the end of the Eocene was probably, as was the earlier uplift in the southern Diablo Range, a result of thrust emplacement of a Franciscan wedge at depth. This is, in turn, inferred to be a subduction-related process. A change from oblique to normal subduction is believed to have taken place near the end of the Eocene, although there was a net decrease in the normal component of plate convergence through the Oligocene and a consequent steepening of the angle of subduction (Page and Engebretson, 1984). The approach of the spreading ridge to the continental margin (Engebretson and others, 1985) would have resulted in the subduction of young, buoyant lithosphere. No definite cause and effect relations can be established, but it seems probable that regional tectonic activity from the latest Eocene into the Oligocene was related to these plate tectonic events. Furthermore, Paleogene deformation in the northern Diablo Range seems to be consistent with subduction-related tectonics.

The late Eocene regression is, coincidentally, approximately correlative with an interval of lowered sea level in the lower part of supercycle "TA4" of Haq and others

(1987) (pl. 2). The pattern of the regression—that is, strongly developed in the north and south, weakly developed on the southeast and west margins, and apparently absent in the deeper parts of the basin—suggests that the local effects of tectonism may have been augmented by a fall in sea level. Tectonism was dominant in the north, in the area of the Diablo Range, and possibly at the south end of the basin. A minor regression is recorded elsewhere along the basin margins where the fall of sea level outpaced basin subsidence, but the record in much of the deeper parts of the basin is not clear.

LOWER OLIGOCENE SEQUENCE

The lower Oligocene sequence is present only in the southern San Joaquin basin. Along the southwest side of the basin, deep-marine deposition continued from the Eocene into the Oligocene with only minor shallowing and the two sequences are not clearly separated. At the south end of the basin, deep-marine deposition resumed after the late Eocene regression, while in the north, an extensive hiatus indicates that the Stockton arch remained a positive area through most of the Oligocene (pl. 2). Eocene and Paleocene units are truncated over the crest of the arch, and later Tertiary nonmarine strata rest directly on Cretaceous rocks (Church and Krammes, 1958). The sea also withdrew from most of the Sacramento basin at the end of the Eocene, leaving only a narrow embayment occupying the former Markeley submarine canyon (Almgren, 1978). Extensive marine deposition was restricted to the southern part of the San Joaquin basin from the Oligocene through the Pliocene. Continued mild uplift of the northern San Joaquin basin and concurrent reverse movement on the Stockton fault during the Oligocene, while subsidence continued in the southern part of San Joaquin basin, was probably a continuation of the subduction-related tectonism that began in the late Eocene.

Oligocene deep-marine deposition in the southern San Joaquin basin was interrupted at mid-Oligocene time by a regression (pl. 2). Evidence for the regression is best developed in the western San Emigdio Mountains at the extreme southwest end of the basin where upper Oligocene rocks of the Temblor Formation overlap Eocene rocks to lie directly on the basement (Nilsen and others, 1973; Lagoe, 1986). Along the west-side fold belt, a thin shallow-water sandstone unit, the Wygal Sandstone Member of the Temblor Formation, occurs within a deep-water shale section (Addicott, 1973; Carter, 1985). A slight angular unconformity is present at the base of the Wygal locally in the fold belt, but the units may be conformable farther east and south (Harding, 1976; Carter, 1985). Evidence for a mid-Oligocene regression elsewhere in the basin is somewhat questionable, although a major mid-Oligocene unconformity is inferred on the margins of the La Honda basin (Stanley, 1985), the offset western continuation of the southern San Joaquin basin.

The mid-Oligocene regression appears to be approximately coincident with a major lowering of sea level at about 29 to 30 Ma (Haq and others, 1987) (pl. 2). The amount of relative sea-level change required in the San Joaquin basin, however—a shallowing from middle bathyal to inner neritic depths (1,500–2,000 m)—is far too much to be accounted for by eustatic sea-level change alone. The encounter of the Pacific-Farallon ridge with the North American continental margin was also at about 29–30 Ma (Atwater, 1970; Atwater and Molnar, 1973). This is, as Stanley (1985, p. 11) termed it, a "cruel coincidence between major eustatic and tectonic events." Uplift of southern California in response to the approach of the spreading ridge, as proposed by Nilsen (1984), may have been felt as far north as the southernmost end of the basin, where it would have caused the uplift of the San Emigdio Mountains area. Farther north, the ridge itself would not have had an effect, but the subduction of young, buoyant lithosphere in the east flank of the approaching ridge might have. The regional tectonic framework in which the uplift took place includes, in addition to the approach of the spreading ridge, a steepening of the angle of subduction of the Farallon plate and consequent southwestward migration of the arc volcanism into Nevada (Snyder and others, 1976; Cross and Pilger, 1978), as well as the onset of extensional deformation in the Basin and Range (Zoback and others, 1981). Broad uplift of the region between the trench and the westward-advancing volcanism and Basin and Range extension might, then, be considered a subduction-related event, but the exact cause of the abrupt uplift at the west margin of the San Joaquin basin is not known. It may have been a continuation of uplifts that started at the end of the Eocene, which were probably related to the subduction of young lithosphere and to the change from oblique to normal subduction. If the mid-Oligocene regression was basinwide, as it appears, and not just restricted to the south and west margins, it may be due to a combination of eustatic sea-level change and local tectonism.

UPPER OLIGOCENE SEQUENCE

The upper Oligocene sequence is also restricted to the southern San Joaquin basin, although alluvial sedimentation of the Valley Springs Formation began in the northern part of the basin in the late Oligocene. The sequence in the Kettleman Hills area is atypical (pl. 2) in that sedimentation continued into the Miocene after a minor reversal of the regressive trend at the Oligocene-Miocene boundary.

A regression near the end of the Oligocene produced unconformities around the northwest, north, and east margins of the basin and a shoaling at the south end. Part of the Coalinga-Kettleman Hills area remained high well into the early Miocene (Kuespert, 1983, 1985). An unconformity at the base of the Agua Sandstone Bed of the Santos Shale Member of the Temblor Formation[3] truncates older units in the northern Temblor Range (Heikkila and MacLeod, 1951; Carter, 1985; Pence, 1985), but the units become conformable farther southeast and the Agua pinches out. Where present, the Agua indicates a shallowing, similar to that of the Wygal Sandstone Member, from bathyal to neritic depths (Carter, 1985). In the Bakersfield arch area, the deep-water Vedder Sand is disconformably overlain by shallow-water basal deposits of the Jewett Sand (Bartow and McDougall, 1984).

There is apparently no major eustatic sea-level event that correlates with this final Paleogene regression, although a lowstand at about 25 Ma (Haq and others, 1987) is close (pl. 2). The amount of relative sea-level change that took place would rule out eustasy as a primary cause anyway. The encounter of the Pacific-Farallon ridge with the North American margin had, by late Oligocene time, resulted in the formation of a triple junction at the continental margin. However, this triple junction was still located off southern California (Atwater, 1970), and triple-junction tectonism should not have affected the San Joaquin basin at that time. Uplift near the end of the Oligocene at the south end of the basin was probably a continuation of the southern California uplift; elsewhere, it may have been a continuation of seemingly subduction related tectonism that began earlier in the Oligocene. This tectonism seems to have had the most pronounced uplift effects on the west or northwest side of the basin and lesser effects elsewhere.

An indirect effect of the regional tectonism and associated volcanism in central Nevada that began in the Oligocene was the deposition of rhyolitic ash-flow and air-fall tuffs in the northern Sierra Nevada and adjacent northern San Joaquin basin (Slemmons, 1966). Rare tuffs date from before 30 Ma, but more widespread pyroclastic deposition in the latest Oligocene (Dalrymple, 1964) was concurrent with the beginning of alluvial sedimentation (Valley Springs Formation) that continued into the Miocene and may indicate uplift east of the basin.

[3]This awkward name was introduced into the literature by Maher and others (1975); it is little used.

NEOGENE AND QUATERNARY

LOWER AND MIDDLE MIOCENE SEQUENCE

The regression near the end of the Oligocene was followed by a marine transgression in the southern part of the basin that began near the Oligocene-Miocene boundary and brought about a rapid return to the bathyal or abyssal depths of the Oligocene (Bandy and Arnal, 1969). Lavas, mostly of basaltic and andesitic composition but including minor dacitic lava, erupted at the southeast end of the basin in the Tehachapi-San Emigdio Mountains area at about 22–23 Ma and flowed westward or northwestward across the strandline (Nilsen and others, 1973). Volcanism and extensional tectonism also characterized the late Oligocene-early Miocene history of the western extension of the San Joaquin basin in the Santa Cruz Mountains (Stanley, 1985). In the northern part of the San Joaquin basin, extensive alluvial sedimentation of the Valley Springs Formation continued into the Miocene.

The apparent coincidence between extensional tectonism, as shown by basin subsidence and volcanism, and passage of the Mendocino triple junction has been noted in the section on "Plate Tectonics." The northward progression of volcanism and its association with triple-junction migration, of which the volcanic rocks in the San Emigdio Mountains are one element, has been well documented by Johnson and O'Neil (1984). The case is not so clear for basin subsidence, however, because the data of Bandy and Arnal (1969) indicate that the south end of the basin was as deep during the Oligocene, before passage of the triple junction, as it was in the Miocene, after passage of the triple junction. Nevertheless, geohistory analysis (Olson and others, 1986) indicates that the basin subsided rapidly after the brief regression that intervened between the late Oligocene and early Miocene deep-basin intervals. Extensional tectonism is demonstrated by a latest Oligocene and early Miocene episode of normal faulting recorded in the San Emigdio Mountains (Davis, 1986; Hirst, 1986). The most likely explanation for extensional tectonism and basin subsidence beginning about 24 Ma at the south end of the basin is the passage of the Mendocino triple junction that created an extensional stress regime in its wake (Dickinson and Snyder, 1979; Ingersoll, 1982). Alluvial sedimentation of the Valley Springs Formation, however, is too old and too far north to have been related to triple-junction passage and is more probably a result of increased sediment supply due to uplift in the source area.

The Valley Springs Formation in the northern San Joaquin Valley, and its associated rhyolitic pyroclastic deposits, was succeeded in the middle Miocene by extensive andesitic volcaniclastic sediments of the Mehrten

Formation. There is no apparent angular discordance between the two units (Marchand, 1977; Grant and others, 1977), although there is an unconformity with as much as 120 m of erosional relief in the eastern part of the outcrop area (Gale and others, 1939). Although there was obviously no major tilting of the northwest edge of the basin at this time, there may have been regional uplift of the Sierra Nevada and the San Joaquin basin without a southwest tilt. A minor regressive pulse, evidenced by a nonmarine tongue (the lower variegated unit) in the Temblor Formation, can be seen on the west side of the basin as far south as Kettleman Hills north dome (pl. 2). This regressive pulse suggests a regional uplift of the northern part of the basin.

Deposition of the lower and middle Miocene sequence ended after a regression that is apparent along the southeast margin of the basin and in the northern Temblor Range segment of the west-side fold belt (pl. 2). The Olcese Sand forms a clastic wedge of shallow-marine and nonmarine sandstone between the deeper water Freeman and Round Mountain Silts in the Bakersfield arch area (Addicott, 1970; Bartow and McDougall, 1984). Abrupt changes in foraminiferal faunas suggest the presence of a disconformity, at least locally, within the Olcese near Bakersfield (Bartow and McDougall, 1984). A nonmarine conglomerate unconformably overlies older Miocene rocks in the Tehachapi and San Emigdio Mountains area (Nilsen and others, 1973; Bartow and McDougall, 1984). In the northern Temblor Range area, an unconformity truncates early Miocene and older rocks over fold crests and is overlain by a shallow-marine sandstone, the Relizian-age Buttonbed Sandstone Member of the Temblor Formation (Dibblee, 1973b; Harding, 1976). The Buttonbed is absent farther southeast, but an unconformity is present between Saucesian and Relizian-age units in structures along the west side of the San Joaquin Valley (Harding, 1976). Still farther south in the southern Temblor Range, the lower Miocene is generally too deeply buried to determine the presence or absence of an unconformity with any confidence; however, in the offset western extension of the southwestern San Joaquin basin in the Santa Cruz Mountains, there is a widespread unconformity at the top of the Saucesian (Stanley, 1985).

The unconformity at the top of the lower and middle Miocene sequence provides conclusive evidence of the earliest en echelon folding along the southwest margin of the basin (Harding, 1976) that can be stratigraphically dated at a minimum age of 16–17 Ma (pl. 2). The west-side folding is probably a result of the initial stages of San Andreas wrench faulting. The unconformity in the Santa Cruz Mountains area, together with the regressive clastic wedge on the east side of the San Joaquin basin and the unconformity in the Tehachapi-San Emigdio area, provides evidence of regional tectonism (Olson and others, 1986; Dickinson and others, 1987) that probably cannot all be ascribed to wrench tectonism. It has been suggested that this early middle Miocene uplift was an isostatic response to the northward movement of the Mendocino fracture zone, which marked the northern edge of a slab of young, buoyant lithosphere, under the basin (Loomis and Glazner, 1986). This is an appealing idea, but it requires a shallow subduction angle so that the subducted plate is in contact with the overlying lithosphere under the basin and can, therefore, affect the overlying plate isostatically. The distribution and timing of magmatism in the western Cordillera indicates much steeper subduction by the middle Miocene (Coney and Reynolds, 1977; Keith, 1978). Paleomagnetic data indicate that much of the clockwise rotation of the Tehachapi Mountains occurred in the early Miocene (Plescia and Calderone, 1986), presumably under right-lateral shear stress after passage of the Mendocino triple junction. To what extent this may have influenced uplift near the end of the early Miocene is not really known. The problem remains unresolved.

MIDDLE AND UPPER MIOCENE SEQUENCE

Deposition of the middle and upper Miocene sequence began during a rapid subsidence. Shallow-marine transgressive sandstone was deposited at the base (Buttonbed Sandstone Member of the Temblor Formation on the west side and the upper part of the Olcese Sand on the east side). Sporadic influxes of coarse clastic sediments at the southeast, south, and west basin margins fed deep-sea fan systems (Stevens sandstone of local usage) in the deep-basin areas (MacPherson, 1978; Webb, 1981). The sequence is characterized, however, by its thick accumulation of fine-grained siliceous sediment (mostly included in the Monterey Formation). The transgression reached its greatest areal extent at about mid-Mohnian time, resulting in broad, shallow shelves along the north and east basin margins (Graham and others, 1982). A thin marine unit in the subsurface at the Chowchilla gas field (about 70 km northwest of Fresno) has yielded late middle Miocene(?) diatoms (J.A. Barron, written commun., 1986). This unit is the northernmost marine Miocene deposit in the San Joaquin basin and very probably represents the approximate northern limit of the middle Miocene transgression. The siliceous lithology of the Monterey-type sediments and their high component of pelagic organisms are due to a combination of broad shelves that caused terrigenous sediment to be trapped in shallow estuaries or lagoons (Graham and others, 1982) and prolific middle Miocene diatom productivity caused by changes in oceanic circulation (Ingle, 1981; Barron, 1986).

The middle Miocene transgression approximately coincides with a eustatic highstand of sea level shown by Haq and others (1987). High sea level may well be the primary factor in the widespread transgression, but the basin also appears to have reached its maximum depth at progressively later times northward (pl. 2). This northward progression suggests that tectonism also played a part and that the northward migration of the Mendocino triple junction may have induced a northward-moving wave of basin subsidence in the San Joaquin basin.

Beginning near the end of the middle Miocene, nonmarine, coarse clastic sediments derived entirely from Coast Range sources were deposited along the northwest side of the San Joaquin basin. These alluvial fan deposits are included in the Oro Loma Formation (Briggs, 1953) and the Carbona unit of Raymond (1969); the latter was mapped as late Miocene and early Pliocene(?) fanglomerate by Bartow and others (1985) (pl. 2). The base of the Carbona unit is dated by vertebrate fossils at 10 Ma (Raymond, 1969; Bartow and others, 1985), but Lettis (1982) suggested that the Oro Loma might be older because it apparently does not contain detritus from the nearby Quien Sabe Volcanics, which range in age from 10.7 to 7.5 Ma (Prowell, 1974; Drinkwater, 1983). Nevertheless, because the Oro Loma and the Carbona have very similar lithologies and are in the same stratigraphic position on the east flank of the Diablo Range, they probably record the same tectonic event. This event must have begun at, or shortly before, 10 Ma and indicates the beginning of Neogene uplift of the Diablo Range and exposure of the Franciscan core. The uplift seems to have begun in advance of the northward-migrating Mendocino triple junction, using either the global-circuit reconstructions of Atwater and Molnar (1973) or the hot-spot method of Engebretson and others (1985). The eruption of the Quien Sabe Volcanics, on the other hand, was approximately coincident with the passage of the triple junction and is one further element in the northward progression of volcanic events (Dickinson and Snyder, 1979; Johnson and O'Neil, 1984).

Deposition of the middle and upper Miocene sequence was interrupted along the southeast margin of the basin by a brief regression near the middle Miocene-late Miocene boundary. An unconformity at the base of the nonmarine Chanac Formation, or its marine equivalent the Santa Margarita Formation, truncates older Miocene units (Bartow and McDougall, 1984). This unconformity indicates a local uplift of the southern Sierra Nevada and Tehachapi Mountains that may have been the first pulse of the gradually accelerating late Cenozoic uplift of the Sierra Nevada. Hay (1976) first proposed that late Cenozoic uplift of the Sierra Nevada began earlier in the south and he also pointed out the relation between the timing of that uplift and the evolution of the San Andreas transform, but it was Crough and Thompson (1977) who proposed what is probably the most likely mechanism for the uplift. That mechanism was thermal thinning of the lithosphere following the northward migration of the Mendocino triple junction and the end of subduction (see section on "Regional Tectonics").

The regressive phase of the middle and upper Miocene sequence was characterized by an increase in terrigenous material, along with a shallowing of the basin. Shallow-marine sandstone (Santa Margarita Formation) was deposited on the north and east side of the restricted marine basin and nonmarine sediments (Chanac Formation) were deposited on the southeast side. The middle and upper Miocene sequence is separated from the overlying upper Miocene, Pliocene, and Pleistocene sequence by an unconformity around the margins of the southern San Joaquin basin, but deposition was apparently continuous in the center of the basin. A local unconformity within the nonmarine Mehrten Formation along the northeast margin of the basin (Wagner, 1981) may correlate with the unconformity in the marine section farther south.

The late Miocene regression in the San Joaquin basin was approximately synchronous with tectonic events in the surrounding regions that are not precisely dated, but that seem to cluster at about 10 Ma. The regression also correlates with a pronounced fall in sea level at 10 to 11 Ma on the Haq and others' (1987) eustatic sea-level curve (pl. 2). In the Basin and Range province, there was a clockwise change in the direction of least-principal stress (from west-southwest–east-northeast to west-northwest–east-southeast) at about 10 Ma, which is consistent with the superposition of right-lateral shear in that region (Zoback and others, 1981). An apparently synchronous event was the accelerating uplift of the Sierra Nevada (Christensen, 1966; Huber, 1981). Folding along the southwest side of the San Joaquin basin, on the other hand, has been apparently continuous since the early middle Miocene; there has been no particular change in rate, merely a shift from one structure to another in a general basinward progression (Harding, 1976).

The cause of tectonic activity at about 10 Ma is unclear, partly because the possible changes in plate motion at that time are also unclear, as discussed in the section on "Plate Tectonics." An acceleration in Pacific-North American relative plate motion might well have been an influence, but the imprecision in the timing of that change makes it difficult to relate it to specific tectonic events in central California. Regardless of plate motions, however, there was an acceleration of slip rates on the San Andreas fault through the Miocene, particularly the late Miocene (Huffman, 1972; Graham, 1978), probably due to increased coupling between the Salinia terrane west of the fault and the Pacific plate. A resulting gradual increase in tectonic activity throughout the region may have initiated a regression, but it is probable that the fall in sea level at 10 to 11 Ma was a strong contributing factor.

UPPER MIOCENE, PLIOCENE, AND PLEISTOCENE SEQUENCE

Deposition of the upper Miocene, Pliocene, and Pleistocene sequence in the southern San Joaquin basin was started with transgression of the Etchegoin Formation over older Miocene units. Alluvial fans and deltas prograded basinward as abundant coarse detritus was delivered to the basin from the rising Sierra Nevada on the east, the San Emigdio Mountains on the south, and eventually from the Coast Ranges on the west. Alluvial fan deposition along the southeast margin of the basin (the Kern River Formation) began about 8 Ma, although there was no comparable event at that time in the northeast. The coarse clastic sediments of the Kern River may, then, be evidence that the accelerating late Cenozoic uplift of the Sierra Nevada began earlier at the south end of the range. In the northeastern part of the basin, some fine arkosic alluvium of late Pliocene age from the Sierra Nevada (Laguna Formation) is virtually unweathered and resembles modern rock flour produced by glaciers eroding granitic rocks (Marchand, 1977). The presence of this rock-flour-like alluvium suggests a late Pliocene onset of alpine glaciation in the Sierra Nevada.

The final regression, which began in the latest Miocene, was greatly accelerated through the Pliocene as progradation of coarse clastic sediments continued from all sides of the basin, and it culminated with the final retreat of the sea by about the end of the Pliocene. The stratigraphic sequence in the center of the southern San Joaquin basin records a gradual shallowing from shallow-marine shelf (Etchegoin Formation) through restrictive marine to brackish facies (San Joaquin Formation) and finally to freshwater fluvial and lacustrine facies (Tulare Formation) in the late Pliocene to middle Pleistocene. This shallowing took place even as the basin continued to subside, rapidly in the western part of the Maricopa-Tejon subbasin. The San Joaquin and Tulare are conformable in the center of the basin and both interfinger eastward with Kern River alluvial fan deposits, but an unconformity is present at the base of the Tulare along the west and south margins of the basin. The San Joaquin-Tulare conformable contact at Elk Hills, and presumably elsewhere at the south end of the basin, is dated at 2.5 to 3.0 Ma (C.A. Repenning, written commun., 1980), which is somewhat older than the equivalent boundary farther north.

A general decline in sea level after a highstand at about 5 Ma (Haq and others, 1987) may have contributed to the regression during the Pliocene, but it is more likely that the principal cause was tectonism. Increasing tectonic activity and uplift to the east, west, and south, especially following the change in relative plate motion and the consequent increase in compression normal to the San Andreas fault at about 5 Ma, resulted in greatly increased sedimentation that outpaced basin subsidence. Contributing factors in the transition to a nonmarine basin in the late Pliocene were the progressive closing off of the basin's western outlet by continued northwestward migration of the Salinia terrane, and folding and uplift in the Temblor and Diablo Ranges. The unconformity at the base of the Tulare Formation is due to continued deformation of the western and southern basin margins in response to compression across the San Andreas fault. In the San Emigdio Mountains, major north-directed thrusting on the Pleito fault system produced the coarse alluvial sediments of the Tulare Formation (Davis, 1983, 1986). The rapid subsidence of the western part of the Maricopa-Tejon subbasin during the Pliocene and early Pleistocene, which was concurrent with the shallowing trend, was probably due to tectonic loading by thrust plates at the south margin of the basin.

UPPER PLEISTOCENE AND HOLOCENE DEPOSITS

Late Quaternary sedimentation in the San Joaquin basin consisted of episodic deposition of alluvial sediments at the valley margins (Marchand and Allwardt, 1981), which grade basinward into a more continuous section containing a series of lacustrine deposits (Croft, 1972; Marchand, 1977). By about the middle of the Pleistocene, the San Joaquin basin drainage outlet was closed or nearly closed, and the impounded drainage created a large lake, evidenced by a widespread lacustrine clay—the Corcoran Clay Member of the Tulare (Frink and Kues, 1954) and Turlock Lake (Marchand and Allwardt, 1981) Formations (fig. 3). Disappearance of the Corcoran lake was approximately coincident with, and was probably caused by, the establishment of the present Central Valley drainage outlet through the Carquinez Strait and San Francisco Bay at about 0.6 Ma (Sarna-Wojcicki and others, 1985). The sedimentary record of the latest Quaternary is similar to that of the middle Pleistocene, but it contains a succession of smaller pluvial lakes.

Tectonism has played an important role in the Quaternary history of the San Joaquin basin. Closing of the valley's drainage outlet and continued uplift of the surrounding ranges that supply sediment to the alluvial basin are the consequences of tectonism, but the Quaternary sedimentary record reflects climatic controls more than tectonic. Cycles of alluviation, soil formation, and channel incision in the Quaternary deposits of the northeastern San Joaquin basin can be correlated with climatic fluctuations and the resultant glacial stages in the Sierra Nevada (Bateman and Wahrhaftig, 1966; Marchand, 1977). A similar cyclical pattern is apparent in the alluvial fan deposits on the west side of the basin that were derived from the unglaciated Diablo Range (Lettis, 1982, 1985). This pattern suggests that the inferred climatic control of sedimentation is more complex than a simple correlation of alluviation event with glacial outwash event; it involves, as well, the effect of climate on rates of weathering and on changing vegetation patterns, and how these factors, in turn, influence sediment supply (Marchand, 1977; Lettis, 1982, 1985). Creation or periodic enlargement of pluvial lakes in the center of the basin can also be correlated with the cyclic alluvial deposits and with Sierran glaciations (Atwater and others, 1986). The appearance and disappearance of these lakes has been dependent on the balance between the inflow volume on one hand, and basin subsidence and the growth of alluvial fan dams on the other.

BASIN EVOLUTION

The Great Valley of California, which is today an alluvial plain surrounded by mountains, was, at the beginning of the Cenozoic, occupied by a marine shelf and slope system that was part of an extensive forearc basin at the west edge of North America (Dickinson and Seely, 1979; Ingersoll, 1979). The forearc basin, which originated in the Mesozoic in a convergent-margin setting, evolved during the Cenozoic into the hybrid intermontane basin in a transform-margin setting that exists today. Each of the five structural regions of the basin, which show differences in style of deformation, have somewhat different tectonic histories as a result of the changes in stress regimes through the Cenozoic. This evolution of Cenozoic stress, discussed separately for each region of the basin in the section on "Geology," is integrated into the generalized summary diagrams of figure 4. Changes in regional stress are closely related in

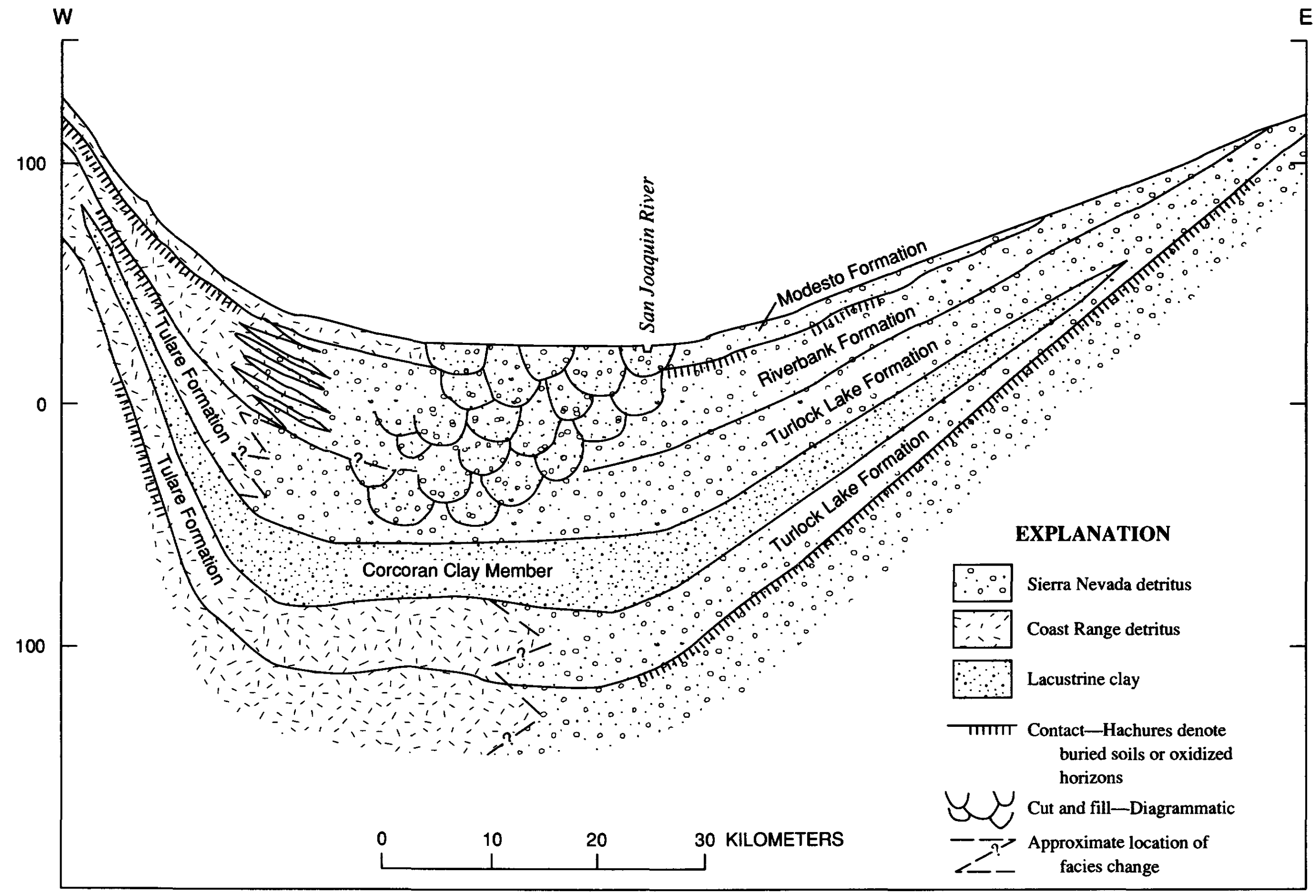

FIGURE 3.—Diagrammatic cross section of the northern San Joaquin Valley showing stratigraphic relations of Quaternary alluvial deposits in the valley subsurface. Modified from Lettis (1982).

space and time to the northwestward migration of the Mendocino triple junction and the consequent evolution of the San Andreas transform. The changing stress regimes and the resulting tectonic changes are reflected in the varying patterns of sedimentation and changing paleogeography during the Cenozoic evolution of the basin.

The discussion that follows, which also serves as a brief summary of some of the main points from foregoing sections of this report, will make reference to a series of nine paleogeographic maps of the San Joaquin basin and surrounding regions. These maps were constructed for fairly narrow time slices of the Tertiary, shown on plate 2 as stippled bands, rather than for broader intervals such as stages (Zemorrian, Saucesian, and so forth) or even epochs, as has commonly been done in the past. This procedure greatly reduces the problem of trying to show too many, often conflicting events on one map, but it has the disadvantage of implying greater precision in correlation, particularly in the earlier Tertiary, than it is presently possible to achieve. The maps were constructed on palinspastic bases that assume 305 km of Neogene right-lateral slip on the San Andreas fault (Clarke and Nilsen, 1973; Graham, 1978) and an unspecified amount of early Paleogene right slip on the proto-San Andreas fault, together with 150 km of Neogene right slip on the San Gregorio fault (Clark and others, 1984). It is also assumed that the original trace of the San Andreas fault was more or less straight and that the present big bend near the south end of the San Joaquin Valley was acquired in the late Neogene and Quaternary. The paleogeography was compiled from published maps and modified to accord with more recent stratigraphic and sedimentologic data. In many cases where data are sparse or even nonexistent, the maps represent the interpretations and biases of the author.

PALEOCENE

The forearc basin that existed through the late Mesozoic and into the earliest Tertiary began to change in the Paleocene, although the basin geometry of the old arc-trench system persisted. The principal factors influencing Paleocene paleogeography were right slip on the proto-San Andreas fault and uplift of the Stockton arch, which together reflect an overall north-south compressive stress (fig. 4*A*). This stress was apparently a consequence of oblique subduction with a northerly to northeasterly convergence direction (Engebretson and others, 1985). The proto-San Andreas fault, which originated in the Late Cretaceous and had, by Paleocene time, produced a continental borderland of small wrench-fault basins in the Salinia terrane (Nilsen and Clarke, 1975), was active through the Paleocene. Shear stress associated with right-lateral faulting may have been responsible for en echelon folding in the northern part of the west-side fold belt (Harding, 1976) and for oroclinal bending or rotation of the southern Sierra Nevada (Kanter and McWilliams, 1982; McWilliams and Li, 1985). At least part of the folding and rotation may have taken place during the Paleocene. Uplift of the Stockton arch and concurrent up-to-the-south movement on the Stockton fault began in the Paleocene and strongly influenced sedimentation patterns in the northern part of the basin.

Figure 5 shows the paleogeography of the San Joaquin basin in the late Paleocene during the transgressive phase of the upper Paleocene and lower Eocene depositional sequence. The northern and eastern parts of the basin were occupied by a marine shelf; deeper marine slope and basinal facies were restricted to the southwest. An upland, probably of low relief, lay to the northeast, and the shelf and slope were largely open to the ocean on the west. Uplift of the Stockton arch produced a broad west-trending peninsula between the San Joaquin and Sacramento basins. It is not known how much of the arch was exposed at this time because erosion has removed Paleocene strata, but it is assumed that some shallow or nearshore marine deposition took place over the west end of the arch. The extent of the Diablo uplift is also not known, but it was probably not large and represented only a portion of the structural high in the subduction complex at the southwest side of the forearc basin that was uplifted with the Stockton arch. At the south end of the basin, the first stages of the oroclinal bending of the southern Sierra Nevada had produced a westward deviation of the southeast-trending shoreline and left the future Bakersfield arch and the Maricopa-Tejon subbasin area emergent.

EOCENE

The Eocene, as a result of recent revisions in Cenozoic geochronology (Berggren and others, 1985), is the longest of the Cenozoic epochs. Although the Paleogene was generally "quieter" than the Neogene, a number of events, including a major regression separating two basinwide depositional sequences, affected the basin during the Eocene. The combined effects of tectonism and eustatic sea-level change resulted in broad fluctuations in the shoreline and produced major changes in paleogeography. Tectonic activity included uplifts in the Diablo Range area in late early and late Eocene, and possibly in the San Emigdio Range area near the end of the Eocene. In the north, uplift was probably in response to northeast-southwest subduction-related compression that might be considered evidence of Paleogene emplacement of a deep-seated Franciscan wedge, whereas in the south, it was probably in response to regional north-south compression (fig. 4*A*).

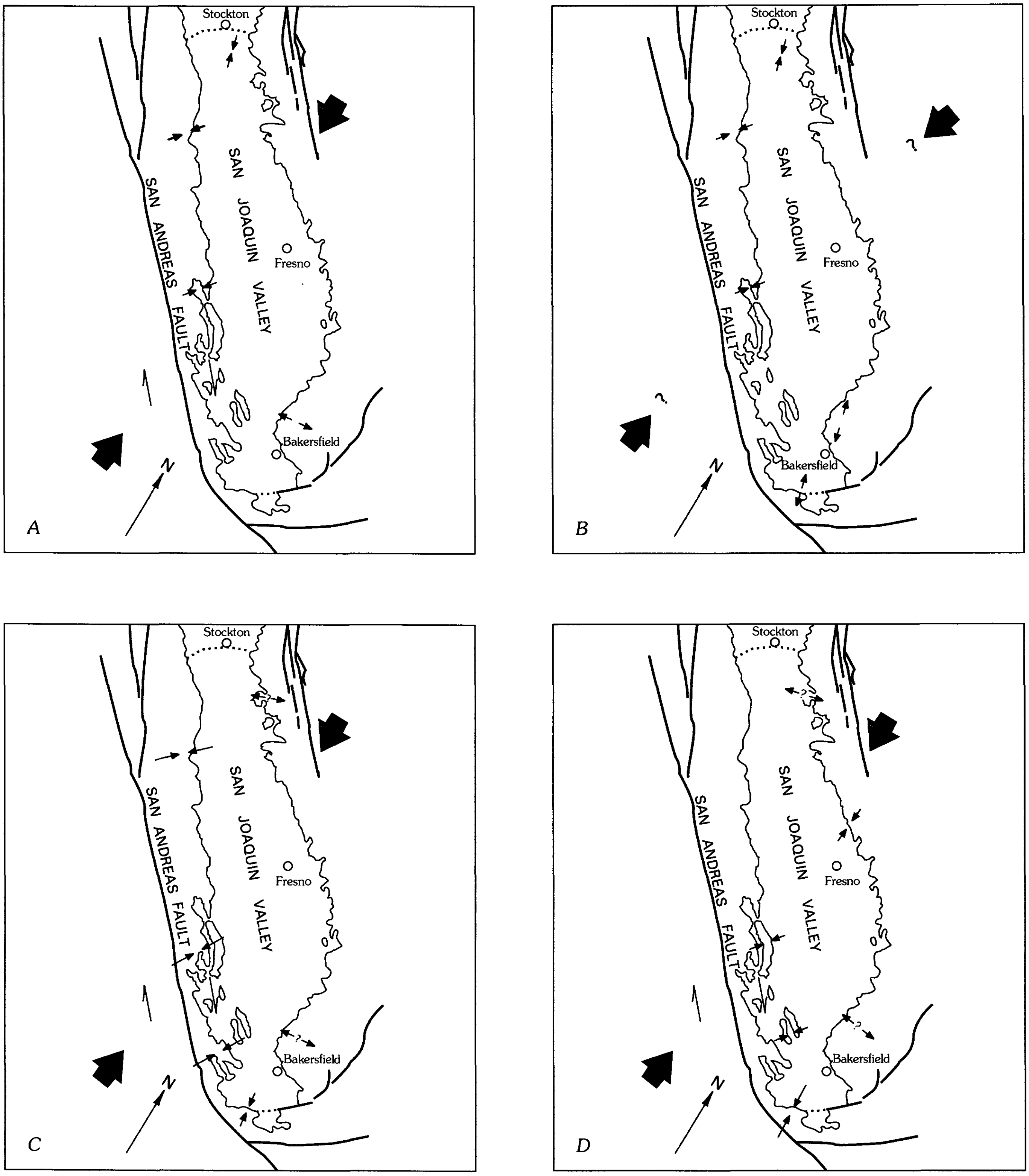

FIGURE 4.—Evolution of regional stress patterns in the San Joaquin Valley area. *A*, Early Paleogene. *B*, Late Oligocene-early Miocene. *C*, Late Miocene-early Pliocene. *D*, Late Pliocene-Quaternary. Edge of present valley alluvium and present major faults generalized from figure 1 for location. Small arrows indicate inferred local stress, large arrows indicate inferred overall compressive stress, paired half-arrows indicate shear couple; queried where uncertain.

A major regression occurred at the end of the upper Paleocene-lower Eocene depositional sequence. This regression was largely a result of eustatic lowering of sea level that left the marine basin greatly restricted (fig. 6). Although their presence somewhat speculative, large deltas are inferred to have prograded westward across the basin from the central Sierra Nevada, which was the principal source of Eocene sediment. Parts of the subduction complex at the west side of the basin were emergent and contributed some sediment, and Salinia terrane highs were emergent to the southwest (Nilsen and Clarke, 1975). At the beginning of the ensuing transgression, basal sands containing Franciscan detritus onlapped the formerly emergent areas on the west side of the basin. Much of the formerly emergent area at the south end of the basin, including the Bakersfield arch, was also inundated. A condensed section in the lower part of the Kreyenhagen Shale (Milam, 1985) immediately above the basal sand of the Eocene depositional sequence is an indication of a rapid transgression.

The point of maximum transgression for the entire Tertiary was reached at middle Eocene time (fig. 7). Widespread pelagic sediments indicate that most of the present-day San Joaquin Valley was covered by deep-marine waters and the basin was largely open to the west, as it had been in the Paleocene. A large deep-sea fan was constructed in the southwestern part of the basin that had its source and proximal part on the Salinia terrane west of the present San Andreas fault (Clarke, 1973; Clarke and Nilsen, 1973). The east side of the basin was fringed by a belt of fluvial and deltaic deposits.

The regressive phase of the Eocene depositional sequence near the end of the Eocene is recorded in the northern part of the basin and at the south end, whereas the record indicates continued deep-water deposition in the central part. Uplifts at this time represent the beginning of tectonic activity that continued into the Oligocene, and probably reflect the approach of the Pacific-Farallon spreading ridge and the transition from oblique to normal subduction (Engebretson and others, 1985).

EXPLANATION

Marine deposits—Solid line indicates inferred shoreline; hachures indicate inferred shelf edge; queried where uncertain

Nonmarine deposition—Dotted line indicates inferred extent; queried where uncertain

Lacustrine deposition

Emergent area—Queried where uncertain

Volcanic center

Faults—Queried where uncertain. Arrows indicate direction of relative movement

Probably active

Possibly active

Future trace of Neogene San Andreas fault

Thrust—Sawteeth on upper plate

Explanation for figures 5 through 13.

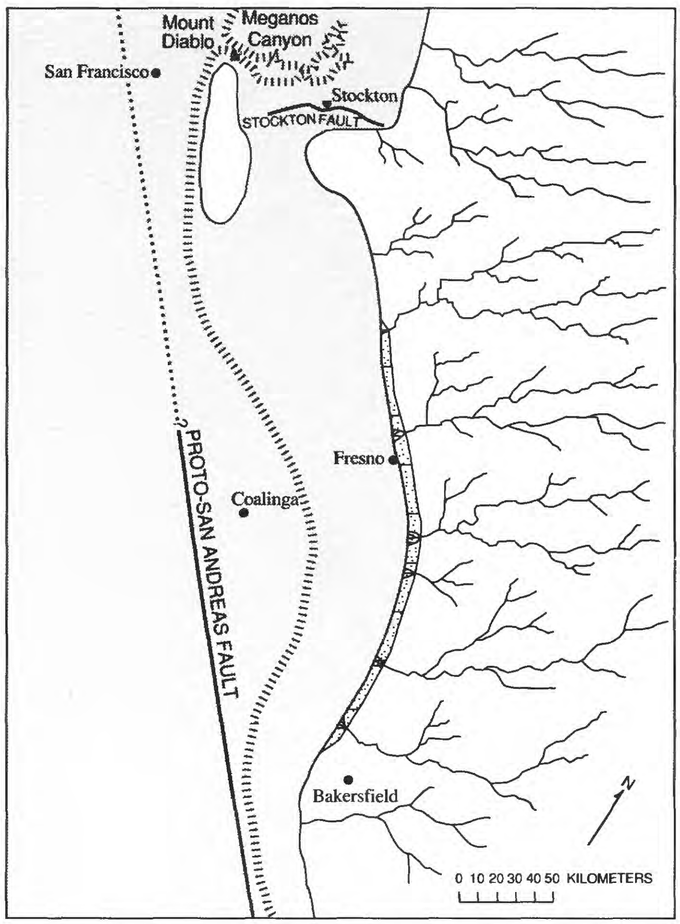

FIGURE 5.—Late Paleocene (about 59 Ma) paleogeography of the San Joaquin basin area. Based on data from Repenning (1960), Clarke and others (1975), Dickinson and others (1979), Nilsen and McKee (1979), Clark and others (1984), Fischer (1984), and Stanley (1985).

OLIGOCENE

The Oligocene marks the onset of change throughout the western United States. Following the change in convergence direction near the end of the Eocene, the angle of subduction steepened during the Oligocene (Page and Engebretson, 1984), leading to changes in the patterns of volcanism (Snyder and others, 1976) and to the initiation of extension in the Basin and Range province (Zoback and others, 1981). The most important event affecting California during the Oligocene was the ridge-trench encounter off southern California that initiated the San Andreas transform system (Atwater, 1970; Atwater and Molnar, 1973). All these events had an effect, whether directly or indirectly, on the San Joaquin basin during the Oligocene and, augmented by eustatic sea-level change, produced major changes in the central California paleogeography.

Continued uplift of the Stockton arch in the northern part of the basin, concurrent with movement on the Stockton reverse fault, and of the San Emigdio area in the south are both indications of a general north-south compression. In the north, the tectonism was presumably subduction related. At the south end of the basin, at least during the later Oligocene, the tectonism was part of a major uplift throughout southern California in response to the ridge-trench encounter (Nilsen, 1984).

The entire northern part of the basin was emergent through the Oligocene, while deep-water sedimentation continued from the Eocene into the Oligocene in the southwestern part. At the time of maximum regression in the middle Oligocene (fig. 8), the Stockton fault was active, the Stockton arch was being eroded, and alluvium was deposited to the north and south of the arch. The earliest rhyolitic tephra were also deposited in the northern Sierra Nevada at about this time. The Diablo Range and probably the northern Temblor Range areas were emergent, so deep-marine deposition was restricted to the southwestern part of the formerly extensive basin. In addition to the nonmarine deposits south of the

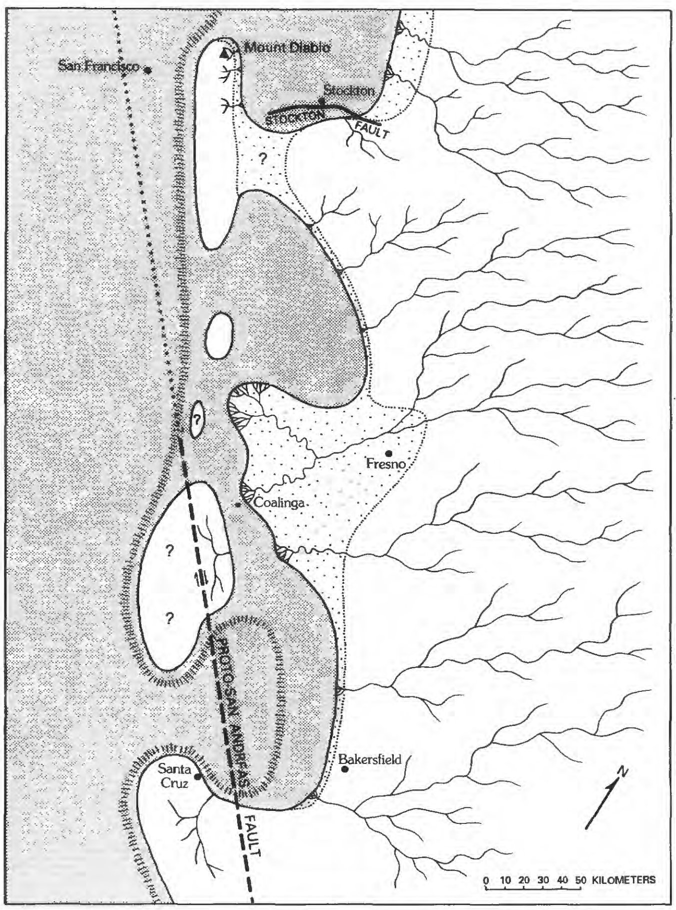

FIGURE 6.—Early to middle Eocene (about 52 Ma) paleogeography of the San Joaquin basin area. See figure 5 for explanation. Based on data from Repenning (1960), Clarke and others (1975), Graham (1978), Graham and Berry (1979), Nilsen (1979), Nilsen and McKee (1979), Slagle (1979), and Stanley (1985).

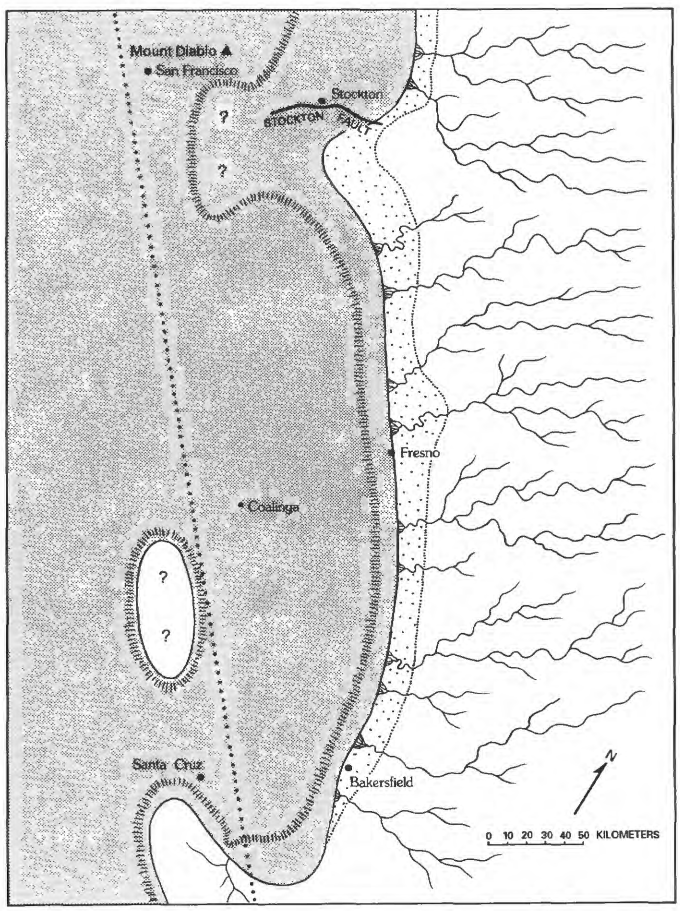

FIGURE 7.—Middle Eocene (about 44–45 Ma) paleogeography of the San Joaquin basin area. See figure 5 for explanation. Based on data from Repenning (1960), Clarke (1973), Clarke and others (1975), Nilsen (1979), Nilsen and McKee (1979), and Palmer and Merrill (1982).

Stockton arch, a narrow fringe accumulated along the east side of the marine embayment, while coarser alluvial fan deposits derived from uplifts to the south accumulated along the south and southeast margins of the basin. A north-south axial profile of the basin floor at this time would start above sea level in the north (probably not more than a few tens of meters) and reach depths of over 1,800 m in the south, illustrating the marked southward tilt of the basin in the Oligocene.

MIOCENE

The evolution of the San Joaquin basin was accelerated by tectonic events of the Miocene, most of which were a result of the northwestward migration of the Mendocino triple junction. The interval during which the triple junction was located opposite the basin nearly coincides with the Miocene epoch (Snyder and others, 1976; Johnson and O'Neil, 1984) (pl. 2). Paleogeographic changes took place at a faster pace, particularly adjacent to the developing San Andreas fault system. Marine deposition was restricted to the southern part of the basin, but extensive nonmarine deposition began in the north. There was also a major change in regional volcanism, as the rhyolitic pyroclastic deposits of the late Oligocene and earliest Miocene were replaced near the end of the early Miocene by reestablished andesitic arc volcanism in the northern Sierra Nevada (Slemmons, 1966; Stewart and Carlson, 1976). The arc volcanism was then progressively shut off from south to north as the Mendocino triple junction migrated northward and cut off subduction (Snyder and others, 1976).

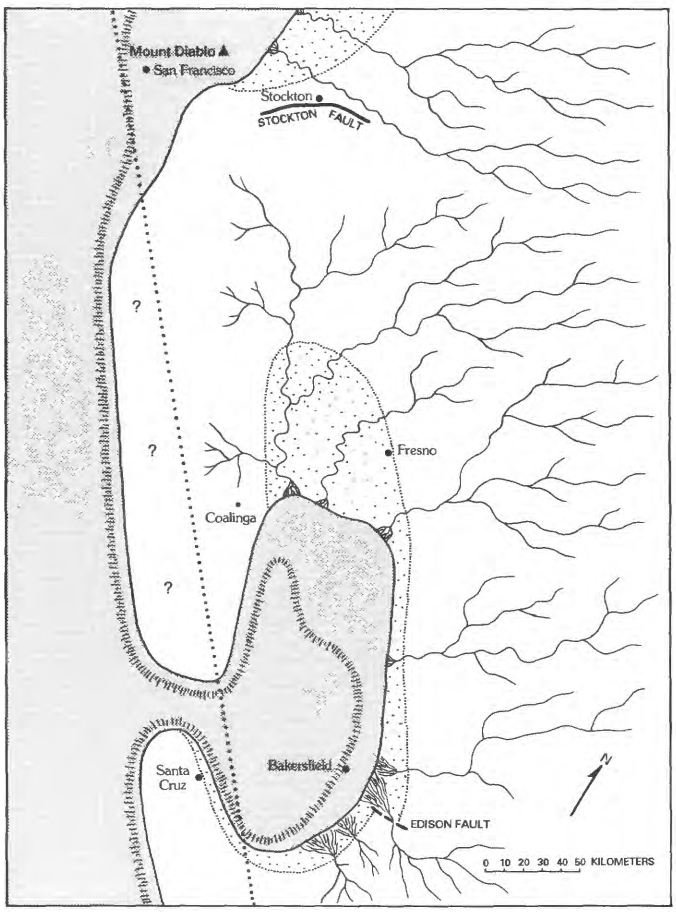

FIGURE 8.—Oligocene (about 30 Ma) paleogeography of the San Joaquin basin area. See figure 5 for explanation. Based on data from Repenning (1960), Addicott (1968), Bandy and Arnal (1969), Greene and Clark (1979), Nilsen and McKee (1979), Nilsen (1984), and Pence (1985).

The patterns of regional stress, which had begun to change in the Oligocene, continued to change through the Miocene. This was first apparent at the south end of the basin where east-west-oriented normal faulting and subsidence, probably beginning in the latest Oligocene, and volcanism in the early Miocene indicate north-south extension (Davis, 1986; Hirst, 1986) (fig. 4*B*). En echelon folding in the west-side fold belt, beginning near the end of the early Miocene and continuing through the Miocene, is a manifestation of a newly established northwest-southeast-oriented shear couple centered on the San Andreas fault system (Harding, 1976). The accelerating uplift of the Sierra Nevada during the late Miocene (Huber, 1981) was accompanied by north-south-oriented normal faulting that indicates minor east-west extension in the southern Sierran block. The Diablo uplift and the eruption of the Quien Sabe Volcanics in the late Miocene are closely associated with the passage of the Mendocino triple junction (Johnson and O'Neil, 1984). The uplift seems to indicate compression, presumably oriented northeast-southwest, and was followed immediately by minor local extension in a developing northwest-southeast shear regime.

The early Miocene marine embayment (fig. 9) was not very different from the Oligocene embayment. The northern Temblor Range area that was briefly exposed at mid-Oligocene time was inundated in the early Miocene, as it had been in the late Oligocene, and the early Miocene strandline advanced even farther eastward onto the southern Sierran block. Nonmarine deposition expanded northwestward as tuffaceous alluvial plain deposits covered the northern basin and Stockton arch areas. The last stages of the previously extensive coarse alluvial fan deposition took place at the south end of the basin.

The paleogeography changed considerably near the early Miocene-middle Miocene boundary (fig. 10). Uplift of the southern part of the basin produced a regression there as alluvial fan and fan-delta deposits prograded basinward. Farther north, however, there was a transgression, as the strandline advanced northwestward onto the Diablo uplift in the Coalinga area and in the Vallecitos syncline. There was probably a shallow seaway trending northwest through the Vallecitos syncline. The initiation of wrench tectonism on the southwest side of the basin resulted in uplifts in the adjacent Salinia terrane and nonmarine deposition in the southern Diablo Range area. The beginning of andesitic volcanism in the northern Sierra Nevada is reflected in the nonmarine volcaniclastic deposits of the northern San Joaquin and Sacramento basins.

After the early to middle Miocene regression, the marine embayment expanded to its Neogene maximum extent, approximately coincident with a middle Miocene highstand of sea level (pl. 2). Marine deposits of late middle Miocene age reach as far north as Chowchilla (70 km northwest of Fresno). The basin axis at that time seems to have been considerably farther east than the present axis, probably because uplift of the southern Diablo Range and consequent sediment influx from the west forced the northern basin axis to the east. In the deep southernmost part of the basin, extensive deep-sea fan deposits were derived from the east, the south, and the southwest.

By late Miocene time (fig. 11) the northward movement of the Salinia terrane, composed of isolated highs surrounded by shallow seas (Graham, 1978), west of the San Andreas fault was beginning to close off the San Joaquin basin on the west. A new seaway had opened through the Priest Valley area west and northwest of Coalinga, but there was no longer a deep-marine outlet to the Pacific Ocean. The deep-marine embayment was becoming more restricted as shallow-marine shelf deposits and nonmarine deposits prograded basinward along the east side of the basin. Sedimentation in the northern part of the basin was still dominated by volcaniclastic sediments derived from the extensive andesitic volcanism in the Sierra Nevada, but the inception of coarse alluvial fan deposition of sediments derived from the Diablo Range on the northwest indicates uplift of that range. Volcanic centers were active in the Sierra Nevada (Moore and Dodge, 1980) and the central Diablo Range.

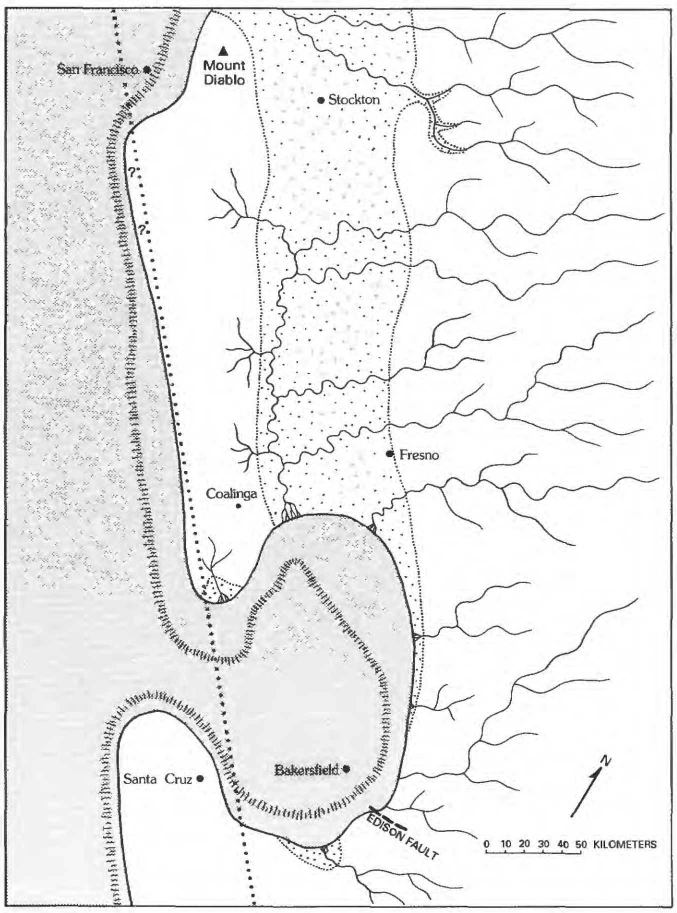

FIGURE 9.—Early Miocene (about 20–21 Ma) paleogeography of the San Joaquin basin area. See figure 5 for explanation. Based on data from Gale and others (1939), Repenning (1960), Addicott (1968), Bandy and Arnal (1969), Graham (1978), Kuespert (1983), Pence (1985), and Stanley (1985).

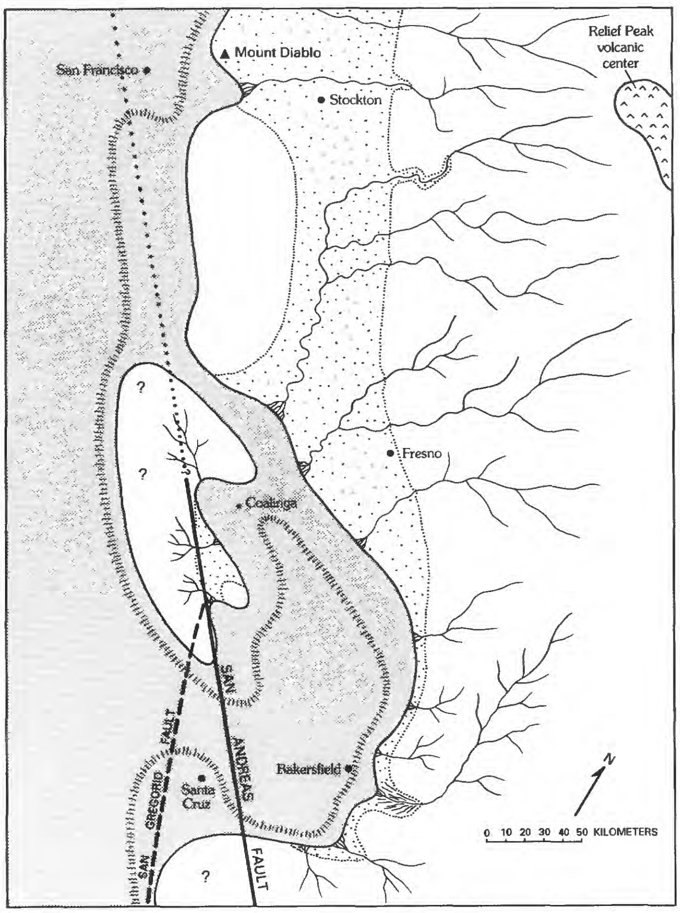

FIGURE 10.—Middle Miocene (about 16 Ma) paleogeography of the San Joaquin basin area. See figure 5 for explanation. Based on data from Repenning (1960), Addicott (1968), Bandy and Arnal (1969), Fritsche (1977), Graham (1978), Cooley (1982), Kuespert (1983), Bate (1984), Bent (1985), Pence (1985), and Stanley (1985).

Flows from the Sierra Nevada centers reached at least to the basin margin along the ancestral Stanislaus and San Joaquin Rivers.

A widespread unconformity in the southern part of the basin marks the culmination of the late Miocene regression (pl. 2). Coarse alluvial fan sedimentation along the southeast margin of the basin in the latest Miocene marks the beginning of the accelerated late Neogene uplift of the Sierra Nevada.

PLIOCENE

Neogene tectonic activity around the San Joaquin basin increased in intensity during the Pliocene, leading to the elimination of the marine embayment by the close of the Pliocene. The San Andreas fault had become the principal element of the transform system by the beginning of the Pliocene (Graham, 1978), and the consequent increase in slip rates caused the Salinia terrane to move rapidly northward, cutting off the southwestern marine connection with the Pacific Ocean.

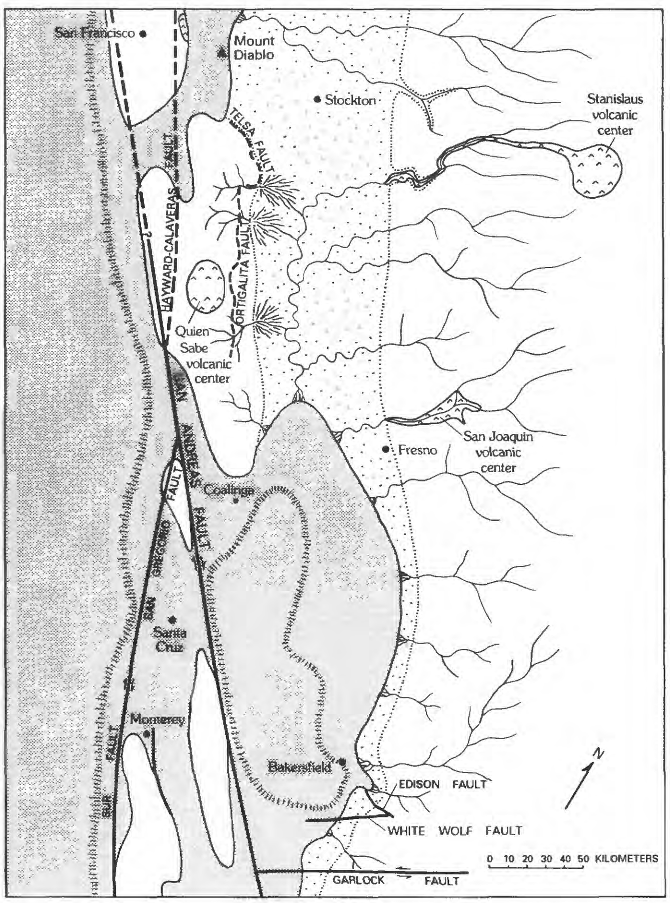

FIGURE 11.—Late Miocene (about 9–10 Ma) paleogeography of the San Joaquin basin area. See figure 5 for explanation. Based on data from Repenning (1960), Addicott (1968), Bandy and Arnal (1969), Fritsche (1977), MacPherson (1978), Phillips (1981), and Graham and others (1982).

The regional stress pattern that originated in the Miocene remained in effect into the Pliocene, with only moderate change (fig. 4*C*). The northwest-southeast shear couple associated with the San Andreas fault extended farther northwest, and there was an increase in compressive stress normal to the San Andreas as a result of changes in plate convergence direction near the Miocene-Pliocene boundary (Page and Engebretson, 1984; Engebretson and others, 1985). This change in plate motions, together with the westward movement of the Sierran block as a result of extension in the Basin and Range province (Eaton, 1979), caused northeast-southwest compressive stress along the west side of the Sierran block and was largely responsible for increased late Neogene deformation in the fold belt, including deep-seated thrust faults (Wentworth and Zoback, 1986; Zoback and others, 1987). Strong north-south compression at the south end of the basin, probably due in part to the developing bend in the San Andreas fault, was responsible for the onset of northward-directed thrusting in the late Pliocene. The increased loading of the south end of the basin by thrust plates was, in turn, probably responsible for the accelerated subsidence of the western part of the Maricopa-Tejon subbasin in the latest Pliocene.

The paleogeography of the Pliocene (fig. 12) differed significantly from that of the late Miocene. The embayment was much smaller and the basin, mostly brackish by this time, was enclosed on the south and southwest. Nonmarine deposits prograded into the shallowing embayment from all sides and the emergent Salinia terrane was transported northwestward to completely close the marine outlet by about the end of the Pliocene. A developing uplift lay south of the basin, while the western part of the Maricopa-Tejon subbasin was subsiding rapidly. A shallow seaway west of Coalinga connected the rapidly shallowing embayment with the Pacific Ocean. In the northern part of the basin, there was an increasing sediment supply to the west-side alluvial fans from the rising Diablo Range. On the northeast side of the basin, a change from volcaniclastic to arkosic alluvium indicates that major Sierran rivers had cut down through the blanket of volcanic rocks. Although alpine glaciers in the Sierra Nevada probably appeared before the end of the Pliocene, there is no direct evidence of glaciation prior to about 2.5 Ma.

PLEISTOCENE

By the beginning of the Pleistocene, the San Joaquin basin was entirely emergent and was largely enclosed by the ice-capped Sierra Nevada on the east and by low hills of the Coast Ranges on the west. The valley itself differed from the present valley principally in having its outlet somewhere in the southwest rather than through the Carquinez Straits to San Francisco Bay, as at present.

Uplift and westward tilting of the Sierra Nevada continued through the Pleistocene, while major deformation and uplift of the Coast Ranges, begun during the late Pliocene, also continued. Regional patterns of stress changed little during the Pleistocene (fig. 4*D*). Northeast-southwest compression normal to the San Andreas fault resulted in the southern part of the west-side fold belt being uplifted as the Temblor Range. The Diablo Range was also uplifted, largely as a whole, with little internal differential vertical movement (Page, 1981). Right slip on the Ortigalita fault is evidence that the northwest-southeast shear was also imposed on the Diablo Range (Lettis, 1982, 1985). A very strong north-south compressive stress at the south end of the valley resulted in overthrusting on the faults of the Pleito system and reverse movement on the White Wolf fault (Davis, 1986).

A major feature of the Pleistocene paleogeography was the large lake, the Corcoran lake, that occupied nearly the whole valley for a brief interval near the middle of the Pleistocene (fig. 13). This lake was the largest and perhaps the earliest of a succession of lakes that occupied the valley during the Quaternary. Alpine glaciers in the Sierra Nevada fed rivers as far south as the Kern River, which deposited an apron of outwash along the east side of the valley and built deltas into the lake. After the withdrawal of the sea from the marine embayment at the end of the Pliocene, the drainage outlet of the valley probably remained along the old Priest Valley seaway for a short time. It seems likely, though, that continued uplift and deformation along the San Andreas fault zone between the the Diablo Range and Gabilan Range to the west would have soon closed this outlet. A possible alternative outlet lay farther south at Bitterwater Valley, where the valley drainage could have crossed the northern Temblor Range (pl. 2) to flow down the now

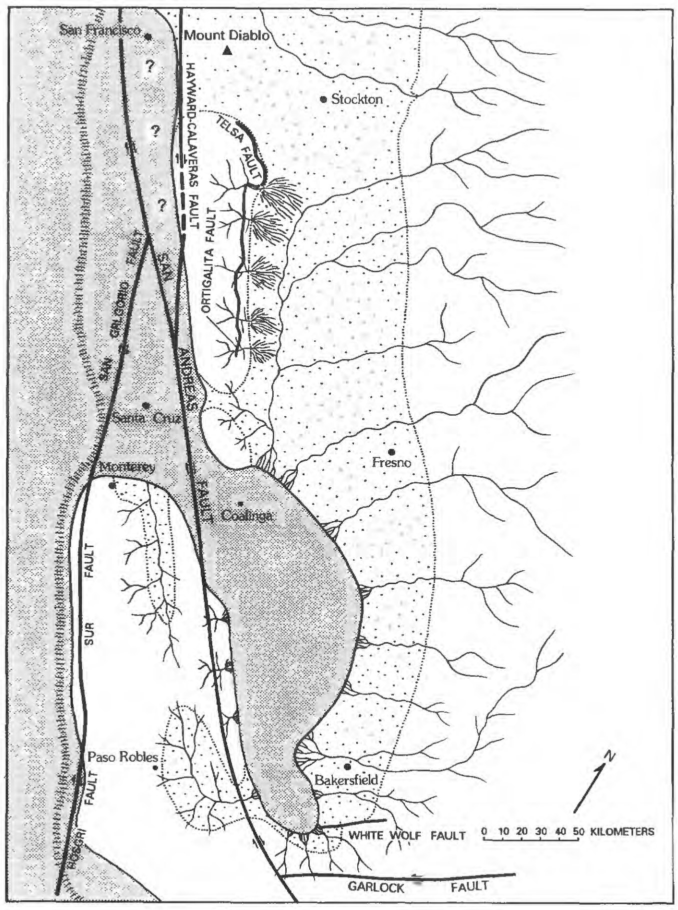

FIGURE 12.—Pliocene (about 3–4 Ma) paleogeography of the San Joaquin basin area. See figure 5 for explanation. Based on data from Repenning (1960), Galehouse (1967), Foss (1972), Cole and Armentrout (1979), and Greene and Clarke (1979).

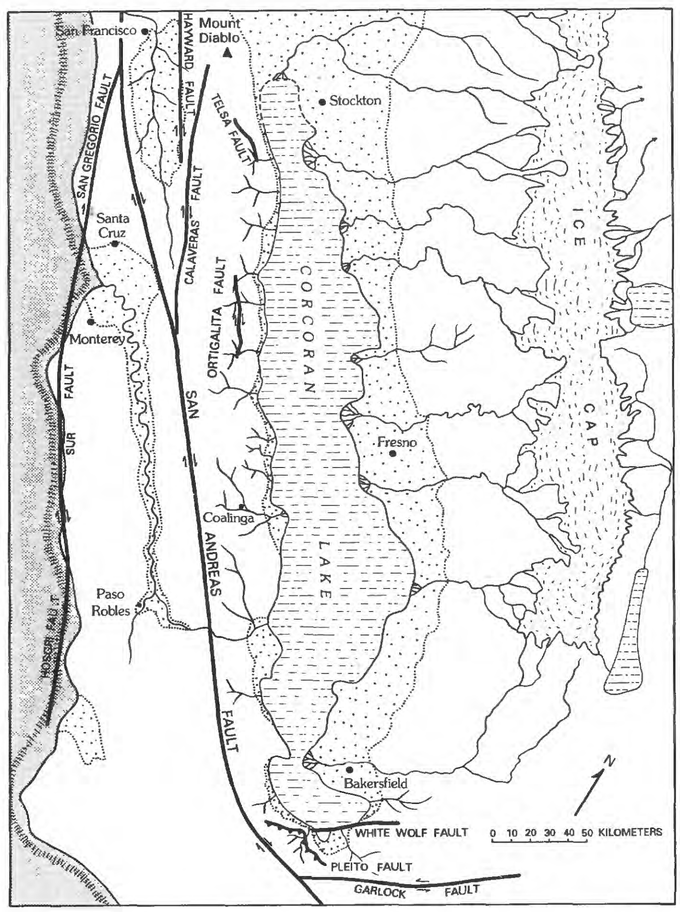

FIGURE 13.—Pleistocene (about 0.6–0.7 Ma) paleogeography of the San Joaquin Valley area. See figure 5 for explanation. Based on data from Wahrhaftig and Birman (1965), Croft (1972), and Page (1986).

underfit Cholame and Estrella Creeks to join the Salinas River north of Paso Robles. This alternative was chosen for the mid-Pleistocene paleogeography of figure 13. In either case, the drainage was at least partly impounded at that time to form the Corcoran lake. The disappearance of the lake (at about 0.6 Ma) is probably a result of the opening of the present Central Valley drainage outlet through the Carquinez Straits (Sarna-Wojcicki and others, 1985).

HOLOCENE

It is commonly assumed that Quaternary tectonism continues unabated to the present day, although the specific evidence is limited. The Corcoran Clay Member of the Tulare Formation today lies at depths of 60 m to more than 200 m below sea level along the synclinal axis of the San Joaquin basin (Miller and others, 1971; Croft, 1972), indicating the magnitude of subsidence in the valley in the past 600,000 years. The sharp upbending of the Corcoran along the west side of the syncline, furthermore, is evidence of Coast Ranges uplift during the same period. Historical subsidence due to fluid withdrawal (Poland and Evenson, 1966), however, tends to mask recent tectonic subsidence. Geodetic measurements also seem to indicate continuing deformation (Burford, 1965; Stein and Thatcher, 1981), although the probable errors inherent in surveying often approach in magnitude the deformations being measured.

The most unambiguous evidence of continuing tectonism is seismicity. Although historical seismicity in California has been dominated by the San Andreas fault system, there have been a few moderate to large earthquakes within the San Joaquin Valley, most notably the 1952 magnitude 7.2 Arvin-Tehachapi and the 1983 magnitude 6.5 Coalinga earthquakes. The 1952 Arvin-Tehachapi earthquake was centered on the White Wolf fault (Oakeshott, 1955; Stein and Thatcher, 1981), and the oblique slip during that event, reverse slip plus a left-lateral component, is evidence of an existing north-south to northeast-southwest compressive stress at the south end of the valley. The 1983 Coalinga earthquake occurred on a northeast-verging thrust fault under the Coalinga anticline (Eaton, 1985b) and may be related to folding and thrusting along the entire west margin of the Central Valley (Wentworth and Zoback, 1986). Lower level seismicity has been recorded from several areas in the San Joaquin Valley (La Forge and Lee, 1982; Eaton, 1985a; Wong and Ely, 1983; Wong and Savage, 1983) and collectively indicates north-south to northeast-southwest compression. Coseismic uplift of as much as 45 cm associated with the Coalinga earthquake (Stein, 1985) demonstrates the continuing growth of young anticlines at the west side of the valley.

CONCLUSIONS

The Paleogene history of the San Joaquin basin was dominated by a tectonic regime resulting from the presence of a subduction zone lying along the continental margin to the west. Oblique convergence in the early Paleogene (Page and Engebretson, 1984) produced a north-south compressive stress and a right-lateral shear couple in the western part of the continent. Right-lateral slip on the proto-San Andreas fault and the northwestward movement of the Salinia terrane into position opposite the south end of the basin (Nilsen and Clarke, 1975; Graham, 1978; Dickinson and others, 1979), large en echelon folds in the southern Diablo Range (Harding, 1976), and clockwise rotation of the southernmost part of the Sierra Nevada (Kanter and McWilliams, 1982; McWilliams and Li, 1985) are all consequences of the early Paleogene stress regime. Although this tectonism shaped the underlying structural framework and strongly influenced Paleogene geography, eustatic sea-level change also had a major influence on the Paleogene sedimentary record and geography. A eustatic fall in sea level was probably the principal cause for the regression at the end of the upper Paleocene and lower Eocene depositional sequence; it was also a contributing factor for each of the other Paleogene regressions, except the final one at the end of the upper Oligocene sequence.

Neogene tectonism and basin evolution were controlled at first by the tectonic effects of the northwestward migration of the Mendocino triple junction along the California continental margin, and they were later controlled by wrench tectonism associated with the San Andreas fault system (Dickinson and Snyder, 1979; Page and Engebretson, 1984). The first effects of Mendocino triple-junction passage, felt at the south end of the basin beginning at about 23–24 Ma, were extension-induced subsidence and volcanism. These events were followed at 16–17 Ma by regional uplift in the southern part of the basin; the uplift seems to have been associated with passage of the triple junction and may have been related, in some way, to the presence of the subducted fracture zone under the basin (Loomis and Glazner, 1986). Continued subsidence after the uplift, accompanied by wrench tectonism in the fold belt, may have been augmented by thermal decay of the subducted plate. The transgression resulting from middle Miocene subsidence was augmented by a eustatic highstand of sea level (Graham and others, 1982). Two lines of evidence from the San Joaquin basin, the inception of en echelon folding near the end of the Saucesian (Harding, 1976) and the distribution and inferred western provenance of Temblor Formation detritus (Graham and others, 1986), indicate that San Andreas fault movement may have begun as early as late early Miocene time along the Temblor Range segment. Folding continued through the later Cenozoic and deformation increased in intensity near the San Andreas fault in the Pliocene and Pleistocene as a result of increased fault-normal compression. However, ongoing deformation at the east edge of the Coast Ranges, and by implication, the basinward expansion of the fold belt, may be considered evidence for deep-seated, eastward-directed thrusting (Wentworth and Zoback, 1986).

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