UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

The Cenozoic evolution of the San Joaquin Valley, California

By

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Open-File Report 87-581

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

1 Menlo Park, California

1987

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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 resting 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, and is in turn subdivided into subbasins by the buried Bakersfield arch. Cenozoic strata in the San Joaquin basin thicken southeastward from about 800 m in the north to over 9000 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 stratigraphic 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 north. The northern Sierran block, the stable east limb of the trough between the Stockton fault and the San Joaquin River, is the least deformed region of the valley. Deformation consists mostly of a southwest tilt with only minor late Cenozoic normal faulting. The southern Sierran block, the stable east limb of the trough between the San Joaquin River and the Bakersfield arch, is similar in style to the northern part of the block, but with 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 trough between the Stockton arch and Panoche Creek, consists of a locally faulted homocline with northeast dips. Deformation was mostly late Cenozoic, complex in its history, and has included up-to-the-southwest reverse faulting. The west-side fold belt, the southwest part of the valley trough 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 folds occur in the northern part of the belt, however, most folding was in Neogene time with the intensity of deformation increasing 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 region is the most deformed part of the basin and has experienced 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 also 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 system; (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 with 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 basin-wide depositional sequences, whereas in the latter, the sequences are shorter and 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, plus the effects of changing eustatic sea level. 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, 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. East-west compression resulting from extension in the Basin and Range Province was an important contributing factor to crustal shortening at the west side of the valley. Eustatic sea-level effects are less discernable in the Neogene, but a middle Miocene high stand 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. The evolution is traced through a series of paleogeographic maps that show the gradual restriction of the marine basin through uplift and emergence of the northern part in the late Paleogene, and closing off of the western outlets in the Neogene, followed by final 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 subdivided 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); 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 both contain closed depressions, and at times receive part of the drainage from the Kings and Kern Rivers.

Geologically, the San Joaquin Valley is an asymmetric structural trough with a broad, gently inclined, and little deformed eastern flank, and a relatively narrow western flank that changes from a steep homocline in the northern part of the valley to a belt of folds and faults in the southern part of the valley (pl. 2). 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 the broad sense, the fill of the San Joaquin sedimentary basin, although this basin is, in a strict sense, a composite of a upper Mesozoic and earliest Cenozoic forearc basin that was largely open to the Pacific Ocean on the west, and a later Cenozoic wrench-fault 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 Jurassic ophiolite under the central and western part 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 rocks below and Great Valley sequence rocks above (Wentworth and others, 1983, Wentworth and others, 1984) (pl. 2A,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 into subbasins by the buried, transverse Stockton arch and Bakersfield arch. The Stockton arch, which is a broad structure bounded on the north by the Stockton fault (pls. 1, 2D) but with a poorly defined southern limit, serves to separate the San Joaquin from the Sacramento sedimentary basin. 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 later. 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. 2D). 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 on 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 by the discovery of oil a few years earlier at McKittrick (1887), Coalinga (1887) and Kern River (1901). Knowledge of the geology of the valley accumulated as oil exploration progressed in the years leading up to and especially 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 recent papers have gone beyond describing the basin stratigraphy and history and have sought tectonic mechanisms controlling 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. More recently, a number of workers (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 1960s, has given a new perspective to the interpretation of regional tectonics (for example: Blake and others, 1978; Howell and others, 1980; Page and Engebretsen, 1984). At the same time, 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 for the 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 of the extensive geological literature on the basin. It incorporates the results of several years of 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 power plants. A basin study approach to understanding regional tectonic history was adopted. This assumes a basic cause and effect relationship 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 terms of both stratigraphy and style of deformation. Stratigraphically, the greatest variation occurred during 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 north. Structurally, the greatest differences are between the west-side fold belt and the relatively undeformed sedimentary cover of the Sierran block on the east side.

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

Northern Sierran block

The northern Sierran block consists of the stable east limb of the valley trough 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 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. 2D). This structure probably formed initially in the latest Cretaceous or Paleocene, perhaps by local thickening of the Cretaceous section, with a major period of uplift in the Oligocene. Its origin will be discussed further in a later section. The structure existed as a low-relief positive feature through most of the Paleogene.

The stratigraphy of the Modesto-Merced area (pl. 3, col.3) is typical of the northeast side of the valley; farther west the stratigraphy is more similar to that of the Orestimba Creek area on the west side of the valley (pl. 3, col. 1). Over the Stockton arch (pl. 1), Paleogene strata are absent and nonmarine later Tertiary strata rest directly on the Mesozoic Great Valley sequence (Church and Krammes, 1958; Bartow, 1985). The Cenozic deposits in this part of the valley are relatively thin (about 1100 m), whereas the underlying Great Valley sequence may be over 3000 m (Hoffman, 1964) (pl. 2A).

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 east side of the valley (Grant and others, 1977; Marchand and Allwardt, 1981). The first evidence of 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 difference 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 lack of traceable markers and erosional relief at the contacts make it difficult to reliably determine gradients or dips in these units. Although there is little good evidence of Oligocene westward tilting, truncation of older units over the Stockton arch indicates uplift of that area. As the southern part of the basin continued to subside during the Oligocene, this produced, in effect, 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 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 continued through the Quaternary, 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). 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.[2] have 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

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

near the tectonic hinge line, was probably approximately coincident with the tilting and 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.

Possibly related features are the numerous northwest trending lineaments observed in the eastern part of the valley (Marchand and Allwardt, 1978; Hodges, 1979). Most of these are probably not faults, but a few display 1-2 m of normal displacement of Pleistocene units (Marchand, 1977). Small normal faults with offsets of a few meters have been observed at a few localities in outcropping 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, but the interpretation of the 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 faults have been recognized in the subsurface of the northern part of the San Joaquin Valley, but the largest, the Stockton fault, bounds the Stockton arch on the north (pl. 2D). The Stockton fault is a south-dipping reverse fault that trends transversely to the regional structure. The fault appears to have had a complex history, but has a total down-to-the-north dip slip of up to 1100 m (Hoffman, 1964). The fault 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 with most of the down-to-the-north offset occurring during the Oligocene (Hoffman, 1964; Teitsworth, 1964; Bartow, 1985). Another west-northwest-trending fault in the Merced-Chowchilla area is based mostly on the apparent offset of the post-Eocene unconformity (Bartow, 1985). Its inferred trace appears to coincide with a diffuse surface lineament visible on satellite imagery (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 northwestward projection of the lineament in the Diablo Range.

Formation of the Stockton reverse 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, suggests east-west to northeast-southwest extension. The normal faulting, however, insofar as it represents flexural stress as the western 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 includes the remainder of the relatively stable and little deformed eastern limb of the valley trough. Its southern boundary is taken as the crest of the Bakersfield arch and the northern boundary is arbitrarity placed at the San Joaquin River (pl. 1).

Both Cenozoic and Mesozoic sedimentary deposits thicken gradually southward to a thickness of more than 5000 m in the area south of Tulare Lake. Cenozoic strata reach a thickness of more than 4500 m, whereas the Mesozoic rocks thin southeastward and pinch out or are truncated against the north flank of the arch (pl. 2D). The stratigraphy of the Bakersfield arch area (pl. 3, col. 9) is typical of the southern part of this area, but Tertiary rocks, particularly the older Tertiary, are not well known in the remainder of the area because of the lack 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 area was characterized by a broadly fluctuating transition between nonmarine deposition on the north and east and a marine basin on the south and west. The Cenozoic stratigraphy in the subsurface of the Hanford-Tulare area (pl. 3, col. 6) probably has elements of 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 northern valley part of the block; differences are principally in degree of deformation rather than in style of deformation. The southwest to west tilt of the Sierran block increases southward so that dips on outcropping Tertiary units in the Bakersfield area average 4-6^{o} in contrast to the 1-2^{o} dips in the north (pl. 2). 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 western edge of the southern Sierra Nevada.

Truncation of Cretaceous and Paleocene(?) strata indicates a tilt event prior to the middle Eocene in 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 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, a broad southwest-plunging ridge of basement rocks, and 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 down dropped more than 600 m. An important exception to the general northwest fault trend is the Poso Creek fault that trends in a general 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, due in part to the fact that Quaternary deposits overlap the Tertiáry 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 in the vicinity of Clovis northeast of Fresno (Page and LeBlanc, 1969). These inferred faults are based principally on surface lineaments and a steeply west-sloping basement surface, but no fault offsets have been convincingly demonstrated.

Many subsurface faults have been inferred by various workers in the area west of the Tertiary outcrop belt. Most of these seem to be small faults with a predominant northwest trend and have been recognized only where the 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. In the vicinity of the town of Pond, a zone of cracks extends to the ground surface and the ground surface 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 markedly upward so that 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 based on apparent offset of Miocene channel sands, but later (Webb, 1981) re-interpreted 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 based on seismic-reflection profiles and oil well data for a proposed nuclear power plant site astride the northern segment of the fault (Los Angeles Department of Water and Power, 1975) concluded that the sense of movement has been normal (down-to-the-east) and that there was no evidence of lateral displacement. This study apparently did not consider the possibility of reverse movement. The geometry of the Greeley structure, however, as seen on seismic reflection records, 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 relationship 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 part of the block where the normal faulting was mostly late Cenozoic in age, it appears to have been mostly Miocene or older in the south. 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 on the basement surface than on late Miocene or Pliocene horizons. Faults with a general north-south trend (NW-SE to NNE-SSW)and those, such as the Poso Creek fault, with a general east-west trend (E-W to ESE-WNW) seem to be similar in that offset decreases upward. In general, north-south trending faults were active in the early Tertiary and again beginning in the late Miocene. East-west trending faults may have had their origin in the latest Oligocene and early Miocene like those at the south end of the basin, as will be shown in a later section, and were probably active until about the late Miocene. The Greeley fault, farther west 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 offset history of the normal faults in the southern Sierran block was, then, concurrent with the late Miocene to recent uplift of the Sierran block (pl. 3), but a significant part was pre-uplift, and faulting seems to have died out 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-south trending normal faults of pre-Miocene age (including northhwest-southeast trending faults like the Greeley and Pond) indicate approximate east-west to northeast-southwest extension in the early Tertiary and 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-southeast trending faults like the Greeley fault. East-west 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 western limb of the valley trough from the Stockton arch in the north to Panoche Creek in the south. It includes the northeast flank of the northern Diablo Range (pl. 1).

The stratigraphy of the Orestimba Creek area and the Los Banos-Oro Loma area (pl. 3, cols. 1 and 2) are representative of the Diablo homocline. Approximately 1400 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). Tertiary marine rocks appear again in the Corral Hollow-Lone Tree Creek area southwest of Tracy. The present Diablo Range is principally a product of 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 relations between the Paleogene Diablo uplift and Stockton arch are unclear, but Neogene structures in the northern Diablo Range appear to have been 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. 2). Subordinate structures are principally faults, but folds associated with the Vernalis and Black Butte faults occur 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 to the northeast of a northwest-southeast-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 relatively 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, which indicates post-Eocene uplift or tilting of the arch. Although the beginning of Neogene uplift of the Diablo Range is evidenced by the appearance of coarse alluvial fan deposits derived from the range in the late middle to late Miocene (pl. 3), 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-southeast-trending fault west of Tracy, (2) the Vernalis fault, a subsurface fault that parallels the Black Butte fault and trends at right angles to the Stockton fault near its west end, (3) the Tesla-Ortigalita fault zone, the western 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, 1979). The age of the Vernalis fault is less well known because it is an entirely subsurface structure. Large offset on the base of the Valley Springs Formation (Bartow, 1985) suggests that most of the movement was Miocene or younger. The upper limit of faulting is not known but, although there is no evidence of Quaternary movement, the fault plane solution for a 1977 M_L 3.5 earthquake near Patterson approximately on-trend to southeast indicates the same syle of faulting (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 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 sugests that it is locally a normal fault (Maddock, 1964; Raymond, 1969). As Maddock points 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 of the dip slip 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 may have been, however, only relatively recently superimposed on the predominant dip-slip.

The history of the Tesla-Ortigalita fault zone is very poorly understood. What today seems to be a more or less continuous fault zone, may be an aggregate of fault segments with different origins and different histories. Some segments may have had their origin 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). Lack of vertical offset of Quaternary units across the southern segment of the fault zone indicate 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. For much of its 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, 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 sub-parallel faults between the Tesla-Ortigalita and the San Joaquin fault zones south of San Luis Reservoir (greatly generalized on plate 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. The resulting faults cause offsets of Quaternary surfaces and 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. 2A,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 wedge of Franciscan (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, but 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 indicates 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 trough from about Panoche Creek on the north to the Elk Hills in the southwesternmost San Joaquin Valley. It 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. 3, cols. 4,5,7,8)--provide some indication of the variation. Total thickness for the combined Mesozoic and Cenozoic section may be over 9500 m near the San Joaquin Valley trough axis. As with the southern Sierra block part of the valley, there is a northward thinning trend for the Cenozoic (pl. 2B,C) and, particularly for the Neogene, a northward trend toward shallower marine and nonmarine facies. Middle Tertiary deposits representing some of the deepest water depths 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 area 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 southeastern boundary of the fold belt is arbitrarily placed east and south of Elk Hills where the fold trends change from northwest-southeast to east-west. The east boundary deviates from the valley trough axis near Cantua Creek and south of Kettleman Hills to include the subdued Turk, Buttonwillow, Bowerbank, and Semitropic anticlines that lie east of the valley axis, but which are structurally more akin to the west-side fold belt than to the relatively 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. 2). 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 Coalinga anticline (May 1983) (Eaton, 1985b) and Kettleman Hills (August 1985) (Wentworth, 1985) are evidence of thrusting beneath major west-side folds and is an indication of the style of Holocene deformation along 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 of a structure that probably formed in the Paleocene or early Eocene (Harding, 1976). Paleogene deformation is difficult to identify in the south, 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 controlled, but eastward-verging thrust faults seem to have formed relatively late in the deformation history in the more tightly folded area near the San Andreas fault (Harding, 1976) and are still active at the western margin of the valley.

A fault along the southwest side of the Semitropic anticline has been interpreted in the past 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 records, suggests 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 record 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. For 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 valley-Coast Range 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 (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. 2D).

The Maricopa subbasin contains the thickest Cenozoic deposits in the San Joaquin basin. Neogene and Quaternary strata are more than 6100 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 deep is not known because few wells have reached the Paleogene and none have reached basement, but more than 1750 m of Paleogene is present in the outcrops near San Emigdio Creek on the south side of the basin (pl. 3, 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 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 (1800 m) were reached in the Zemorrian, Saucesian and Luisian Stages (Bandy and Arnal, 1969). Paleogene nonmarine deposits occur 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 this part of the San Joaquin basin, but there is a general east-west trend along the south margin of the basin. The northwest-southeast fold trends of the west-side fold belt change to west-northwest--east-southeast 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 east-west fold trend. To the north and northeast, the northeast-southwest 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-southeast to east-west trending Edison fault is an older Tertiary normal fault with down-to-the north offset of over 1500 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, has probably had the most complex tectonic history. The earliest evidence of deformation is provided by paleomagnetic data that indicate a clockwise rotation of the Tehachapi Mountains of from 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 after eruption of volcanic rocks in the earliest Miocene (Plescia and Calderone, 1986). The earliest geological evidence of 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 a relatively obscure fault (not shown on pls. 1 or 2) that has been subject to other interpretations (Davis, 1983), so the hypothesized Oligocene thrusting remains somewhat questionable.

Normal faults with an average east-west trend, but ranging from northwest-southeast to northeast-southwest, occur mainly in the subsurface at the south margin of the basin (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[3] (Turner, 1970) and basin subsidence (Hirst, 1986; Davis, 1986). The mostly east-west trending Edison normal fault, as well as other normal faults of general east-west trend in this region of the basin, were also active at this time.

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

The White Wolf fault, which was the locus of the M_L 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 3600 m (Stein and Thatcher, 1981) or possibly more than 4600 m (Davis, 1983). Although seismological data from the 1952

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[3]Ages converted from old to new (1977) constants according to Dalrymple (1979).

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 period of normal faulting (Davis, 1986). There is stratigraphic evidence of continued down-to-the-northwest movement with 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 exists 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, most probably with a general north-south orientation. The Pliocene to Holocene thrust faulting is also 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 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. 3) can be informally subdivided, where they consist mostly of marine deposits, into depositional sequences that are composed of transgressive-regressive couplets which 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 may be considered evidence for external control of the sedimentary record. Although the sequence itself may be considered 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. The location of this basin on an active continental margin, furthermore, virtually guarantees 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 has been 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 the volcanism that occurred 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 would be appropriate to briefly review the plate tectonic events that seem 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. 3). From the Late Cretaceous until about the middle or late Eocene (75-40 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 of time produced a low-angle subduction zone with the 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, with a more normal component of motion relative to North America, supplanted the Kula plate at central California latitudes (Page and Engebretson, 1984). Slow-down 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 in the sense of Dickinson and Snyder (1979) for the whole system of subparallel faults that together 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 17 Ma) with most slip initially on the San Gregorio-Hosgri (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 and is, therefore, not significant (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 is 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 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) show an increase at about 15 Ma, and Cox and Engebretson (1985) infer 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 an artifact 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 10-12 Ma (Huffman, 1972; Graham, 1978).

At 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, and 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 the activity of the proto-San Andreas fault during the Paleocene and possibly early Eocene. Right-lateral strike-slip movement on the proto-San Andreas occurred concurrently 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 Paleocené (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 is unlikely because of the absence of basement arching (pl. 2D). The broad high of Cretaceous rocks made apparent by later truncations is more probably a result of localized structural or sedimentary thickening of the Cretaceous section. Structural thickening, although possible, seems less likely because of the lack of evidence for repetition by thrust faults or other deformation within the Cretaceous section. Sedimentary thickening, on the other hand, seems a better possibility 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 Cretaceous has been removed by post-Eocene erosion (pl. 2D). 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 on the basement surface there in the Cretaceous. As an alternative, the high basement on the north and the increased Cretaceous thickness on the south can be explained by 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. 2A, 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 North American and subduction of young buoyant lithosphere somewhat in advance of the actual arrival of the spreading center 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 southern 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 in the Oligocene is related to the evolution of the arc-trench system and the transition from compression to intra-arc extension and then to back-arc extension as subduction angles steepened and the eastern limit of magmatism 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 between the Basin and Range 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 first conclusive evidence of en echelon folding appears in the record at about the end of Saucesian time (about 16-18 Ma) (Harding, 1976). Additional evidence from the provenance and distribution of Miocene sandstone in the Temblor Range suggests that strike slip may have begun by 17-18 Ma on the central California portion of the San Andreas fault (Graham and others, 1986). This 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 en echelon to it is an indication that they are not purely a response to shear in the San Andreas system. The explanation for the basinward expansion of the Kettleman Hills-Lost Hills part of the fold belt now seems to be that it has formed in response to an eastward advancing thrust front at depth associated with the emplacement of a wedge of Franciscan at the base of the Great Valley sequence (Wentworth and others, 1983) (pl. 2A,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 left-lateral movement on the Garlock fault is assumed to have begun at about the same time. This 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 is probably the cause of 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 are probably not 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 insulates the overlying continental lithosphere, whereas subduction has stopped south of the triple junction which allows 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), and may have contributed to the rapid subsidence of the southern San Joaquin basin (Dickinson and Snyder, 1979; Davis, 1983). Transpression across the fault in Pliocene and Pleistocene time, together with the developing bend in the fault, were probably the principal factors 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, a considerable 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 to 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. Geohistory analysis is, nevertheless, a promising technique and will, ultimately, provide much 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) dessication 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. 1).

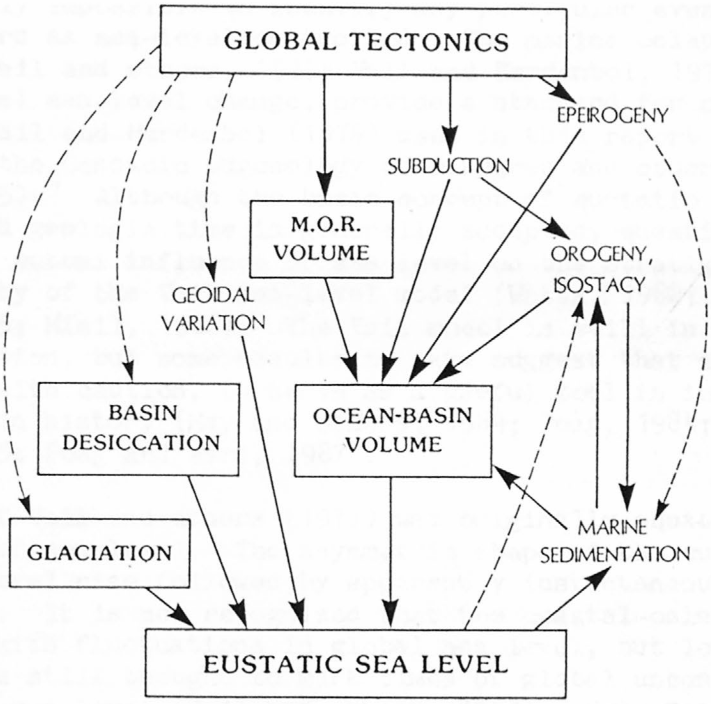

Figure 1.--Interrelations of factors causing eustatic fluctuations of sea level. The major controls on volume changes of the ocean basins and of the global hydrosphere are enclosed in boxes. Ultimately, global tectonics is the overriding influence, either directly (solid lines) or indirectly (dashed lines). M.O.R., mid-ocean ridge. From May and others (1984).

Sea-level change controls sedimentation by controlling the environment of deposition. This is most obvious near the strand line where change in sea level produces lateral shifts of nonmarine and shallow-marine environments. The stratigraphic record of sea-level change on an active continental margin will most 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 with 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 marine onlap curve of Vail and coworkers (Vail and others, 1977; Vail and Hardenbol, 1979), interpreted in terms of global sea-level change, provide a standard for comparison. The onlap curve of Vail and Hardenbol (1979) used in this report (pl. 3) has been adjusted to fit the Cenozoic chronology of Berggren and others (1985), in part after Aubry (1985).[4] 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 in the process of testing and revision, 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 curve of Vail and others (1977) was originally equated directly with relative change of sea level. The asymmetric shape of the curve, with 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 fluctuations in global sea level, but lows in the saw-tooth pattern are still thought to mark times of global unconformities produced by lowered sea level (Vail and others, 1984). Unconformity-bounded sequences of local sections can then be compared with the coastal-onlap curve. Correlation of unconformities between global standard and local sections can be considered 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.

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[4]A later and more detailed curve was published by Haq and others (1987) while this report was in preparation. This newer curve was not adopted here because the time scale used by Haq and others (1987) differs significantly from the scale of Berggren and others (1985) that is used in this report, particularly in the Paleogene. Haq and others have chosen to use low temperature (glauconite) K-Ar dates as well as high temperature dates, even though ages based on glauconite dates are invariably younger than those controlled by high temperature dates. "Because glauconite is not widely regarded as a very reliable chronometer, the systematically younger glauconite dates are strongly suspected to be anomalous" (Berggren and others, 1985, p. 1410, 1413). Although the more detailed sea level curve of Haq and others (1987) may ultimately prove to be useful in understanding San Joaquin basin history, after differences in time scales are resolved, the additional detail is not critical to this report.

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 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 with a low latitudinal temperature gradient and high precipitation (Frakes, 1979; Wolfe, 1978). A rapid deterioration near the Eocene-Oligocene boundary led to glacial conditions in Antarctica in the Oligocene (Frakes, 1979; Mathews, 1984) and generally cooler, dryer global climates. The climate fluctuated in the Neogene, but the overall trend was toward cooler temperatures. Temperatures warmed somewhat in 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). 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, lignite, and 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, and the pluvial climate of the Pleistocene resulted in a series of large lakes in the San Joaquin Valley.

THE SEDIMENTARY RECORD

As can be seen on plate 3, the early Cenozoic sedimentary history of the San Joaquin basin is fundamentally different from that of the later Cenozoic. The early Cenozoic is characterized by a few long-lasting basin-wide depositional sequences, whereas in the later Cenozoic, sequences are shorter and 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 lower order 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 the fill 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. 3). 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 outcrop 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), and 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, as discussed below.

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, and in the central and possibly southern Diablo Range by concurrent en echelon folding associated with movement on the proto-San Andreas fault (Harding, 1976) or by thrusting associated with emplacement of a Franciscan wedge. The angular discordance is always slight or nonexistent, however, and indicates relatively mild deformation.

The unconformity between the Great Valley sequence and the upper Paleocene and lower Eocene sequence correlates with the boundary between global supercycles "Kc" and "Ta" on the coastal onlap curve of Vail and Hardenbol (1979) (pl. 3). The good correlation suggests that sea-level change was a major contributing factor to the regression that produced the unconformity. This is supported by the widespread nature of the unconformity in the San Joaquin basin, coupled with the absence of evidence for strong deformation.

Upper Paleocene and lower Eocene sequence

The deposits of the upper Paleocene and lower Eocene sequence display 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 with 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 amounted to 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 to the basin during latest Paleocene or early Eocene time.

The upper Paleocene and lower Eocene sequence ended with a regression that culminated in a widespread unconformity (pl. 3). 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 where lower Eocene and even Paleocene rocks are locally truncated (Church and Krammes, 1958; Bartow, 1985). From the Kettleman Hills southeastward, the upper Paleocene and lower Eocene and the Eocene sequences appear to be conformable (Church and Krammes, 1959). There is virtually no data on rocks older than late Eocene in the southern Temblor Range. The offset equivalent of these 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 (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 and the Eocene sequences correlates with the boundary between "Ta" and "Tb" global supercycles of Vail and Hardenbol (1979) (pl. 3). 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. There is however, convincing evidence of tectonic activity in central California where there is an angular discordance at the unconformity and where Franciscan detritus is found above the unconformity. 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 fault (Graham and Dickinson, 1978) the belt would lie adjacent to the inferred Paleogene position of the northern end of the Salinia terrane. If 150 km offset is assumed for the San Gregorio-Hosgri fault (Clark and others, 1984), the belt would lie just north of the inferred northern end of the Salinia terrane. This suggests a relationship 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 Diablo Range may, then, have been due to related wrench tectonism that continued into the early Eocene. The role of wrench tectonism at the time is, however, questionable and the uplift might better be considered as evidence of early Tertiary thrust emplacement of a wedge of Franciscan at depth under the southern Diablo Range, just north of the northern 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 was initiated with 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/1000 years for the lower part of the Kreyenhagen. The hiatus and condensed section are results of rapid rise of relative sea level that produced a starved-basin type sedimentation and was, in turn, probably caused by rising global sea level in combination with basin subsidence. Deposition of the bathyal shale that makes up most of the sequence corresponds to a high stand of sea level on the coastal onlap curve of Vail and Hardenbol (1979).

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. 3). There also is some evidence of a minor reversal of the overall Paleogene transgressive trend along the southeastern margin of the basin (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 is the first 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 Formation 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 event near the Eocene-Oligocene boundary may mark the initiation of Oligocene deformation 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 with 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 relatively 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. Paleogene deformation in the northern Diablo Range seems to be, furthermore, consistent with subduction-related tectonics.

The late Eocene regression is, coincidently, approximately correlative with the boundary between global supercycles "Tb" and "Tc" on the Vail and Hardenbol (1979) coastal onlap curve (pl. 3). 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 regressión was 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 following 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. 3). 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, is 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. 3). 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 regression elsewhere in the basin at this time 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 or 30 Ma (Vail and Hardenbol, 1979; Aubrey, 1985) (pl. 3). The amount of relative sea-level change required in the San Joaquin basin, however, a shallowing from middle bathyal to inner neritic depths (1500-2000 m), is far too much to be accounted for by eustatic sea-level change alone. The first encounter of the Pacific-Farallon ridge with the North American continental margin also occurred 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 with the consequent southwestward migration of the arc volcanism into Nevada (Snyder and others, 1976; Cross and Pilger, 1978), and 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 be 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 is basin-wide, as it appears to be, 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. 3) 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 northwestern, northern, and eastern 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 Member of the Temblor Formation 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 near the southeast margin of the basin, the deep-water Vedder Sand is disconformably overlain by shallow-water deposits of the basal Jewett Sand (Bartow and McDougall, 1984).

There is no major eustatic sea level event that correlates with this final Paleogene regression (pl. 3); the amount of relative sea-level change that took place would rule out eustacy 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, but it was still located off southern California (Atwater, 1970) and triple junction tectonism should not have affected the San Joaquin basin. Uplift near the end of the Oligocene at the south end of the basin was probably a continuation of the southern California uplift, whereas elsewhere, it may have been a continuation of tectonism that began earlier in the Oligocene and which seems to have been subduction related. This tectonism seems to have had the most pronounced uplift effects on the west or northwest side of the basin and it had a lesser effect elsewhere.

An indirect effect of 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 beginnings of alluvial sedimentation (Valley Springs Formation) that continued into the Miocene and may indicate uplift east of the basin.

Neogene and Quaternary

Lower and middle Miocene sequence

The late Oligocene regression 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). Volcanic rocks, consisting mostly of basalt and andesite with minor dacite, were 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 strand line (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 as clear for basin subsidence, however, because according to the data of Bandy and Arnal (1969), the southern 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 rapid subsidence did take place following 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 southern 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, with its associated rhyolitic pyroclastic deposits, was succeeded in the middle Miocene by extensive 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. 3), which suggests a regional uplift of the northern part of the basin.

The lower and middle Miocene sequence ended with a regression that is apparent along the southeastern margin of the basin and in the northern Temblor Range segment of the west-side fold belt (pl. 3). 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 on the west side of the basin, 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, but in the offset western extension of the southwestern San Joaquin basin in the Santa Cruz Mountains, there is a wide-spread unconformity at the top of the Saucesian (Stanley, 1985).

The unconformity at the top of the lower and middle Miocene sequence provides the first conclusive evidence of en echelon folding along the southwest margin of the basin (Harding, 1976) which can be stratigraphically dated at a minimum age of 16-18 Ma (pl. 3). The west-side folding is most 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, provide evidence of regional scale tectonism (Olson and others, 1986; Dickinson and others, 1986) 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 movement of the Mendocino fracture zone, with relatively young buoyant lithosphere on its south side, 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

The middle and upper Miocene sequence began with 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) and sporadic influxes of coarse clastics 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), but the sequence is characterized 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 northern and eastern 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.). This is the northernmost marine Miocene 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 with their high component of pelagic organisms is due to a combination of broad shelves that cause 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 coincides with a global rise of sea level shown by Vail and Hardenbol (1979). High sea level may well be the primary factor in the widespread transgression, but a northward progression in the time that the basin reached maximum depth is also apparent (pl. 3). This 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 that were 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. 3). 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 very 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, according to 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 south-to-north progression of volcanic events (Dickinson and Snyder, 1979; Johnson and O'Neil, 1985).

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. Hay (1976) first proposed that late Cenozoic uplift of the Sierra began earlier in the south and he also pointed out the relationship between the timing of that uplift and the evolution of the San Andreas transform system, but it was Crough and Thompson (1977) who proposed the most acceptable mechanism for the uplift, that is, 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 brought an increase in terrigenous material and a shallowing of the basin that culminated on the north and east side of the restricted marine basin with deposition of shallow-marine sandstone (Santa Margarita Formation) and on the southeast with deposition of nonmarine deposits (Chanac Formation). The middle and upper Miocene sequence is separated from overlying upper Miocene, Pliocene, and Pleistocene sequence by an unconformity around the margins of the southern San Joaquin basin, whereas deposition was apparently continuous in the center of the basin. A local unconformity within the nonmarine Mehrten Formation along the northeastern 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 well dated, but that seem to cluster at about 10 Ma. The regression is also approximately coincident with a fall in sea level at about 9 Ma on the Vail and Hardenbol (1979) coastal onlap curve (pl. 3). In the Basin and Range Province, there was a clockwise change in the direction of least principal stress (from WSW-ENE to WNW-ESE) 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 with no particular change in rate, merely a shift of activity from one structure to another in a general basinward progression (Harding, 1976).

The cause of tectonic activity centering on 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 tie to specific tectonic events in central California. Regardless of plate motions, however, there was an acceleration of slip rates in the San Andreas fault through the Miocene, particularly the late Miocene (Huffman, 1972; Graham, 1978), probably due to increased coupling between the Pacific and North American 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 9 Ma was a strong contributing factor.

Upper Miocene, Pliocene, and Pleistocene sequence

The upper Miocene, Pliocene, and Pleistocene sequence in the southern San Joaquin basin was initiated 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 Range 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 southern end of the range. In the northeastern part of the basin, fine arkosic alluvium of Pliocene age from the Sierra Nevada (Laguna Formation) is virtually unweathered and resembles modern rock flour produced by glaciers eroding granitic rocks (Marchand, 1977). This suggests a Pliocene onset of alpine glaciation in the Sierra Nevada.

The final marine 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, leading to the final retreat of the sea by about the end of Pliocene time. 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 fresh-water fluvial and lacustrine facies (Tulare Formation) in the late Pliocene to middle Pleistocene, even though the basin continued to subside--rapidly so in 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 occurs 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 2.5-3.0 Ma (C.A. Repenning, written commun., 1980), which is somewhat older than the equivalent boundary farther north.

Global falls in sea level at 6.5 Ma and at 3.7 to 2 Ma (Vail and Hardenbol, 1979), though separated by a brief rise, may have contributed to the late Miocene and Pliocene regression, but it is more likely that the principal cause was tectonism. Increasing tectonic activity and uplift on east, west, and south, especially following the acceleration of slip rate on the San Andreas fault beginning at about 5 Ma, resulted in greatly increased sedimentation which outpaced basin subsidence. A contributing factor in the transition to a nonmarine basin in the late Pliocene was the progressive closing off of the western outlet of the basin 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 continuing deformation of the western and southern basin margin in response to San Andreas transpression. 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 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 alluviation at the valley margins (Marchand and Allwardt, 1981) that grades 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 of the Turlock Lake (Marchand and Allwardt, 1981) Formations (fig. 2). 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 later Quaternary is similar, but with 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 can be recognized in the alluvial-fan deposits on the west side of the basin that were derived from the unglaciated Diablo Range (Lettis, 1982, 1985). This suggests that the inferred climatic control of sedimentation is more complex than a simple correlation of alluviation event with glacial outwash event, and involves, as well, the effect of climate on rates of weathering and on changing vegetation patterns, and the influence of these factors on 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 western 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 regions of the basin, which today exhibit differences in style of deformation, have had 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 here integrated into generalized summary diagrams (fig. 3). Changes in regional stress are closely related in space and time to the northwestward migration of the Mendocino triple junction and the consequent evolution of the San Andreas

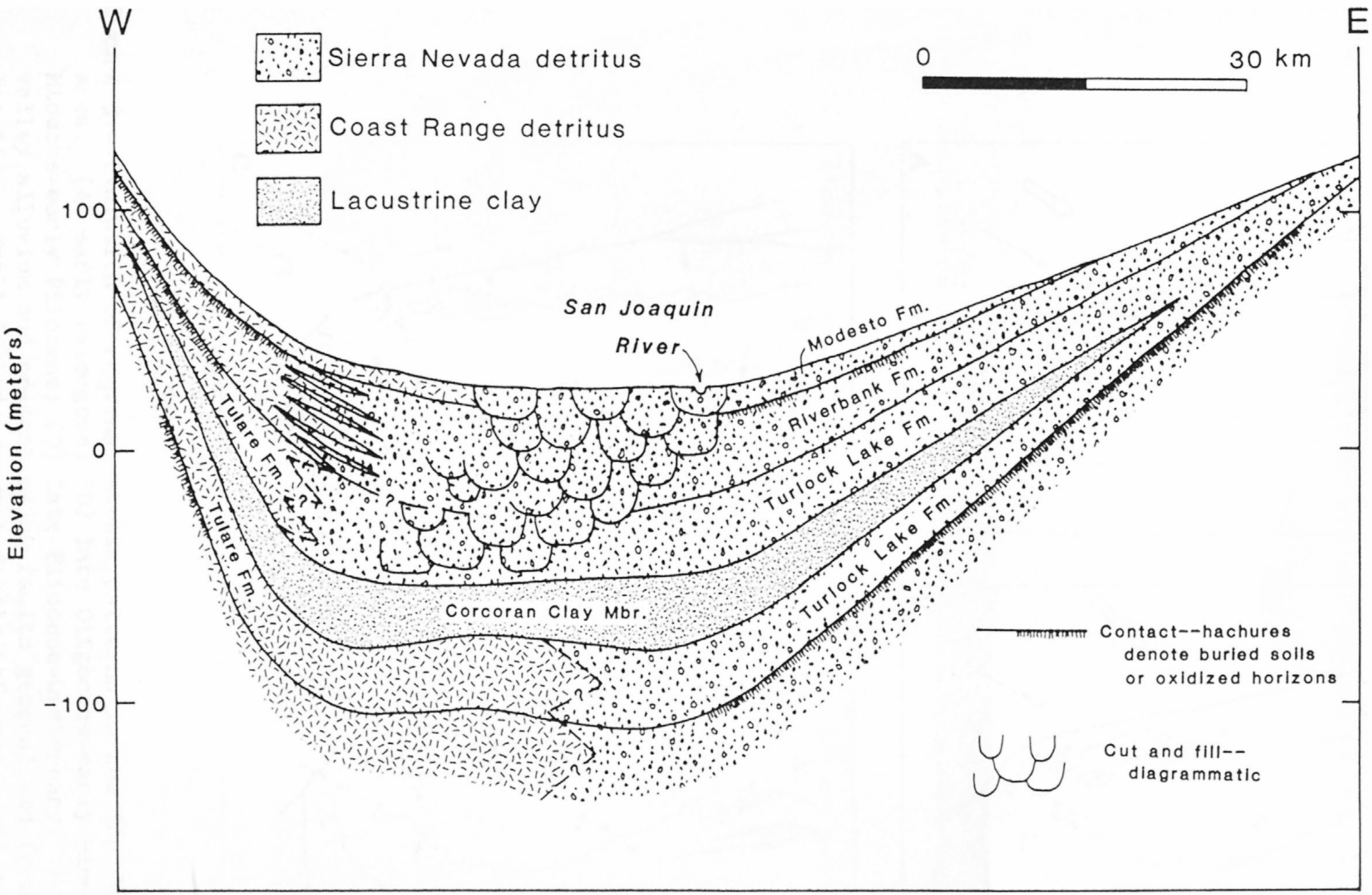

Figure 2.--Diagrammatic cross section of the northern San Joaquin Valley showing stratigraphic relations of Quaternary alluvial deposits in the valley subsurface. Modified from Lettis (1982).

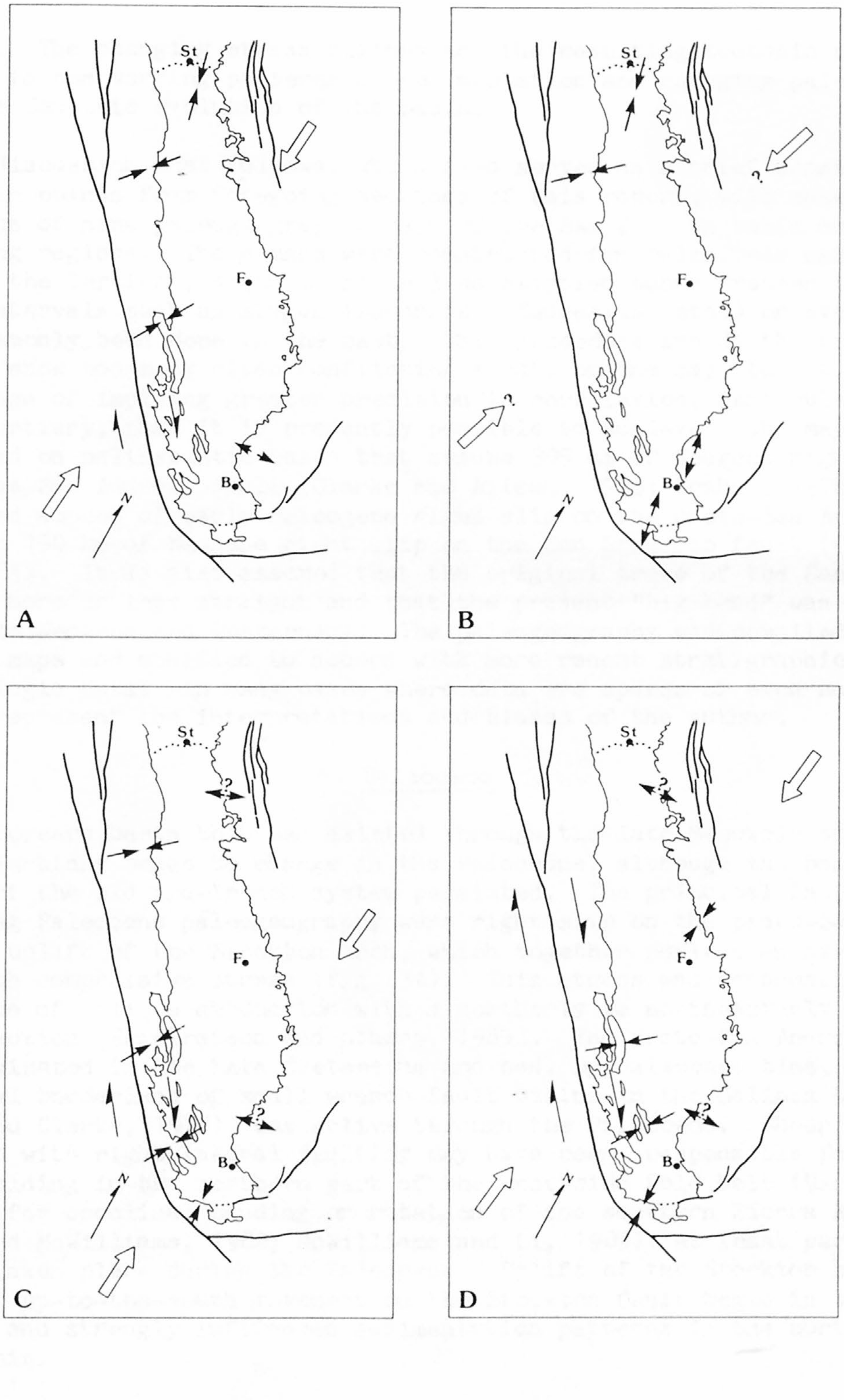

Figure 3.--Evolution of regional stress patterns in the San Joaquin Valley area. (A) early Paleogene; (B) late Oligocene-early Miocene; (C) late Miocene-early Pliocene; (D) late Pliocene-Quaternary. Edge of present valley alluvium and present major faults generalized from plate 1 for location. Small filled arrows indicate inferred local stresses; open arrows indicate inferred overall compressive stress. B, Bakersfield; F, Fresno; St, Stockton.

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 relatively narrow time slices of the Tertiary, shown on plate 3 as stippled bands, rather than for broader intervals such as stages (Zemorrian, Saucesian, etc.) or even epochs, as has commonly been done in the past. This procedure avoids 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), plus an unspecified amount of early Paleogene right slip on the proto-San Andreas fault, and 150 km of Neogene right slip on the San Gregorio fault (Clark and other, 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" 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 had 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. 3A). 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 which 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 4 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

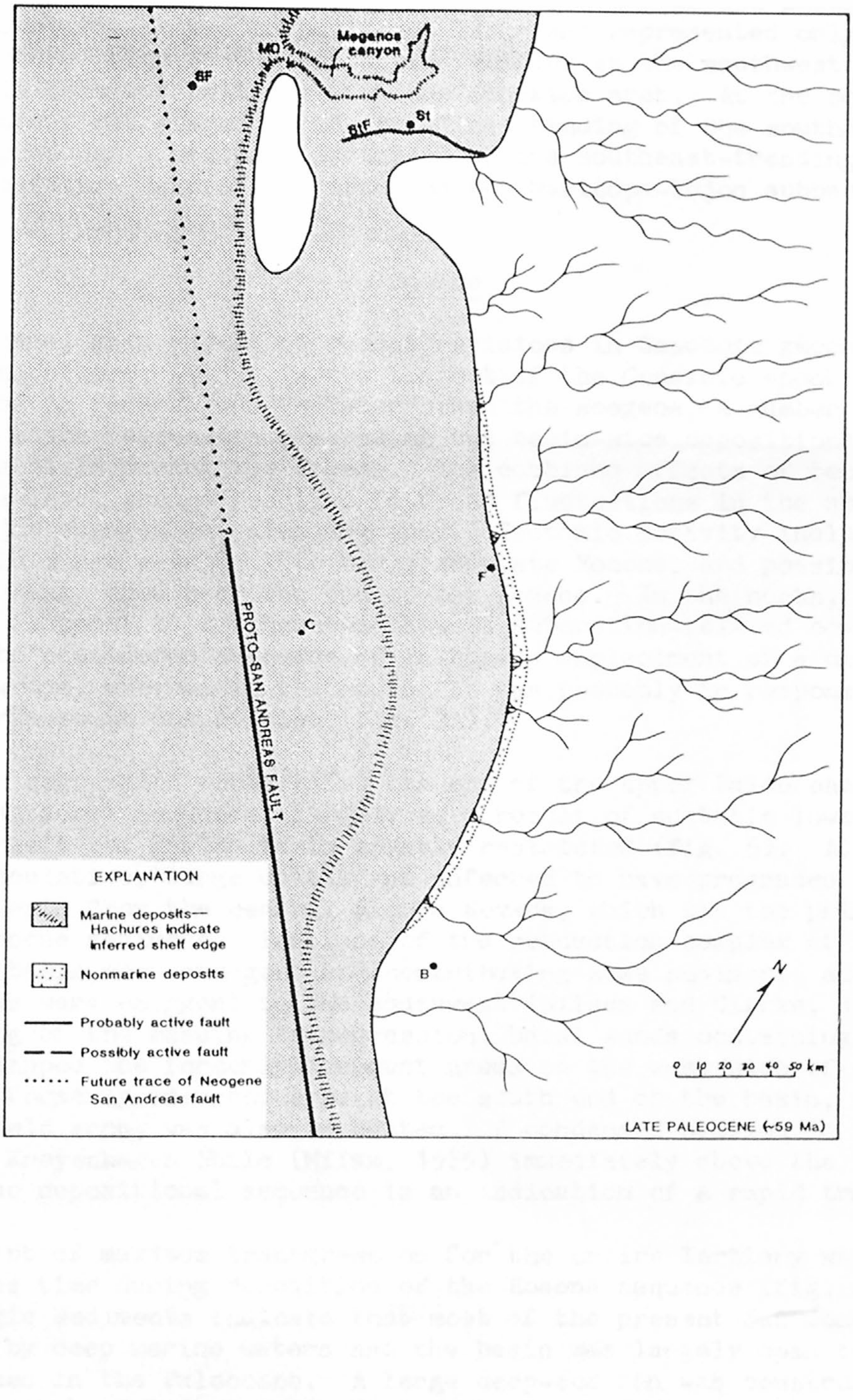

Figure 4.--Late Paleocene (about 59 Ma) paleogeography of the San Joaquin basin area. B, Bakersfield; C, Coalinga; F, Fresno; MD, Mt. Diablo; SF, San Francisco; St, Stockton; StF, Stockton fault. Based on data from Repenning (1960), Clarke and others (1975), Dickinson and others (1979), Nilsen and McKee (1979), Clark and others (1984), Fischer (1984), and Stanley (1985).

between the San Joaquin and Sacramento basins. It is not known how much of the arch was exposed at this time because later erosion has removed Paleocene strata, but it is assumed that some shallow or near-shore 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 in general was "quieter" than the Neogene, a number of events, including a major regression separating two basin-wide 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. 3A).

A major regression occurred at the end of the upper Paleocene-lower Eocene depositional sequence, largely as a result of eustatic lowering of sea level, that left the marine basin greatly restricted (fig. 5). Although somehwat 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. Portions of the subduction complex at the west side of the basin were emergent and contributing 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 during deposition of the Eocene sequence (fig. 6). Widespread pelagic sediments indicate that most of the present 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 which 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 relatively extensive belt of fluvial and deltaic deposits.

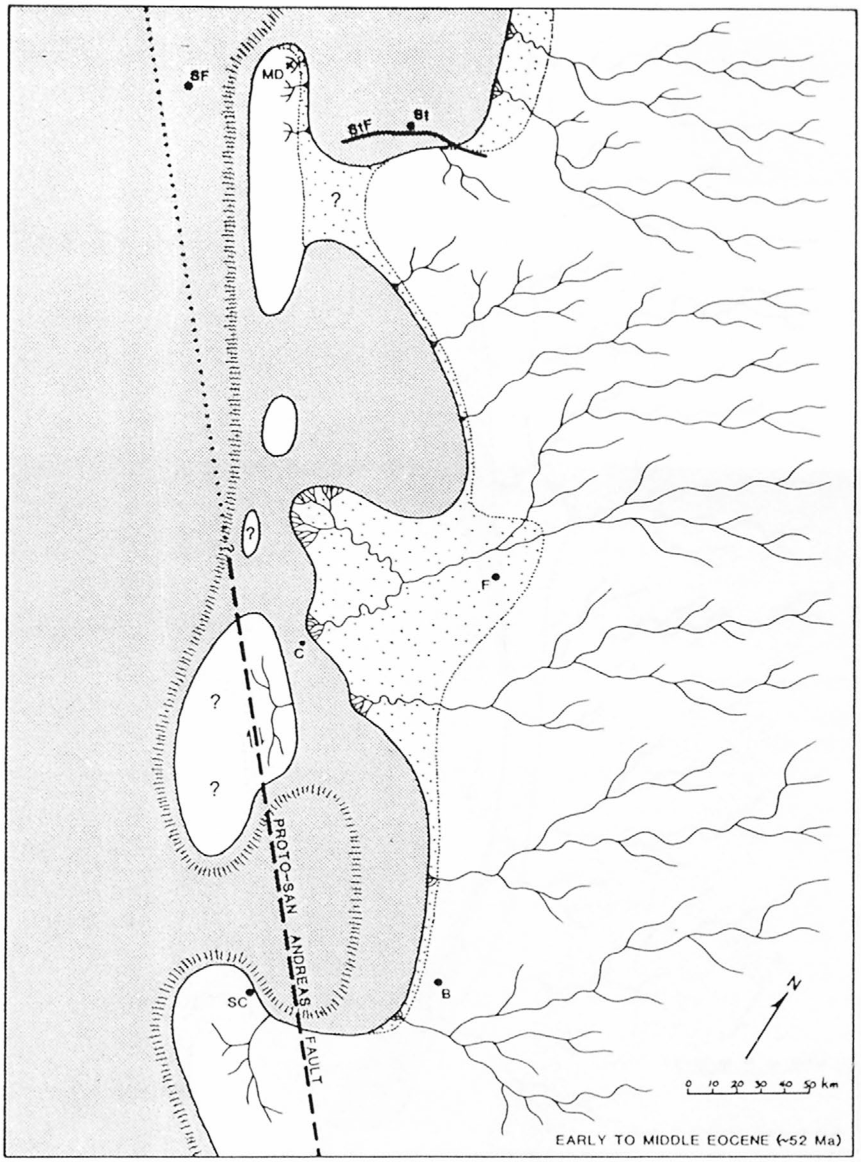

Figure 5.--Early to middle Eocene (about 52 Ma) paleogeography of the San Joaquin basin area. SC, Santa Cruz; other symbols as on figure 4. Based on data from Repenning (1960), Clarke and others (1975), Graham (1978), Graham and Berry (1979), Nilsen (1979), Nilsen and McKee (1979), Slagle (1979), and Stanley (1985).

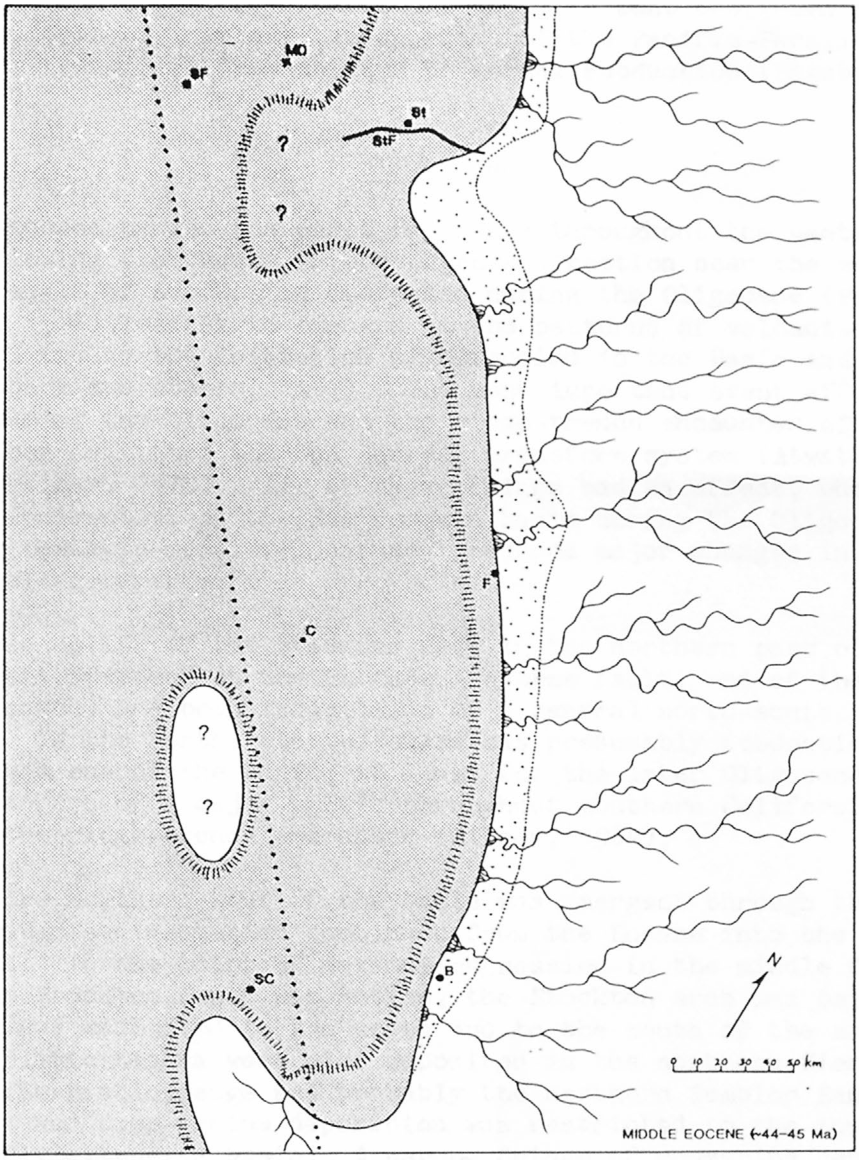

Figure 6.--Middle Eocene (about 44-45 Ma) paleogeography of the San Joaquin basin area. SC, Santa Cruz; other symbols as on figure 4. Based on data from Repenning (1960), Clarke (1973), Clarke and others (1975), Nilsen (1979), Nilsen and McKee (1979), and Palmer and Merrill (1982).

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, while deep-water deposition continued 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).

Oligocene

The Oligocene marked 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 of these things 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, with concurrent 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 southern end of the basin, at least for 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 half of the basin was emergent through the Oligocene while deep-water sedimentation continued from the Eocene into the Oligocene in the southwest. At the point of maximum regression in the middle Oligocene (fig. 7), the Stockton fault was active, the Stockton arch was being eroded, and alluvium was deposited to the north and to the south of the arch. The earliest rhyolitic tephra were also deposited in the northern Sierra at about this time. The Diablo Range and probably the northern Temblor Range areas were emergent and deep-marine deposition was restricted to the southwest part of the formerly extensive basin. A narrow fringe of nonmarine deposits lay 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 margin 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 to the basin in the Oligocene.

Miocene

The evolution of the San Joaquin basin was accelerated by tectonic events of the Miocene, most of which are a result of the northwestward migration of the Mendocino triple junction. The interval during which the triple junction was opposite the basin nearly coincides with the Miocene epoch (Snyder and others, 1976; Johnson and O'Neil, 1984) (pl. 3). Paleogeographic changes took

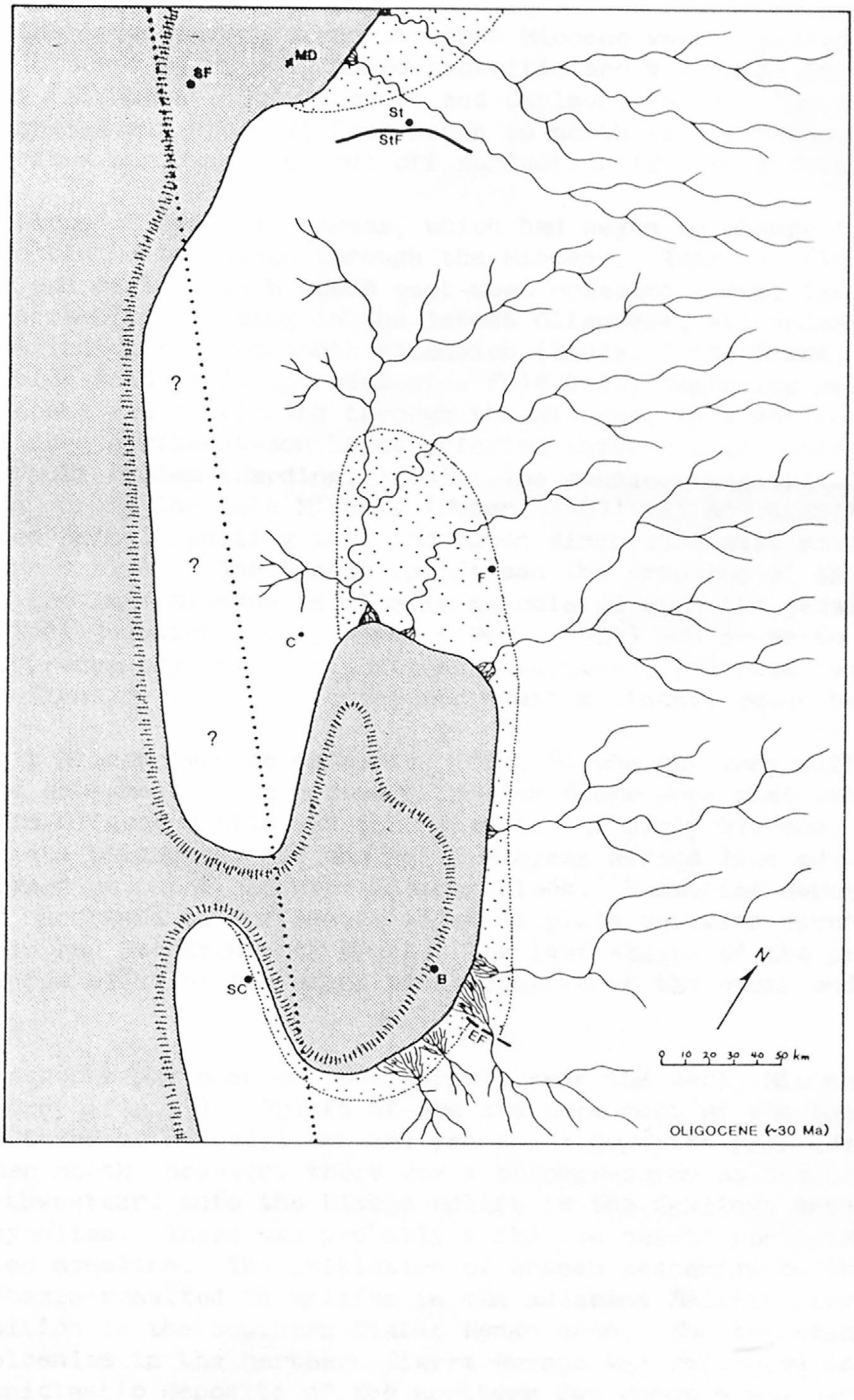

Figure 7.--Oligocene (about 30 Ma) paleogeography of the San Joaquin basin area. EF, Edison fault; SC, Santa Cruz; other symbols as on figure 4. Based on data from Repenning (1960), Addicott (1968), Bandy and Arnal (1969), Greene and Clark (1979), Nilsen and McKee (1979), Nilsen (1984), and Pence (1985).

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. The Miocene also saw 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).

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. 3B). 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 is closely associated with the passage of the Mendocino triple junction (Johnson and O'Neil, 1984) and seems to indicate compression, presumably oriented northeast-southwest, followed immediately by minor local extension in a developing northwest-southeast shear regime.

The early Miocene marine embayment (fig. 8) 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 strand line advanced even farther eastward onto the southern Sierran block. Nonmarine deposition expanded northwestward as tuffaceous alluvial plain deposits covered the southern basin and Stockton arch areas. The last stages of the previously extensive coarse alluvial fan deposition occurred at the south end of the basin.

The paleogeography changed considerably near the early Miocene-middle Miocene boundary (fig. 9). 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 strand line advanced northwestward onto the Diablo uplift in the Coalinga area and in the Vallecitos syncline. There was probably a shallow seaway northwestward from 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 was reflected in the nonmarine volcaniclastic deposits of the northern San Joaquin and Sacramento basins.

Following the early to middle Miocene regression, the marine embayment expanded to its Neogene maximum extent, coincident with a middle Miocene high stand of sea level (pl. 3). Marine deposits of late middle Miocene age reach as far north as Chowchilla (70 km northwest of Fresno). The basin axis at

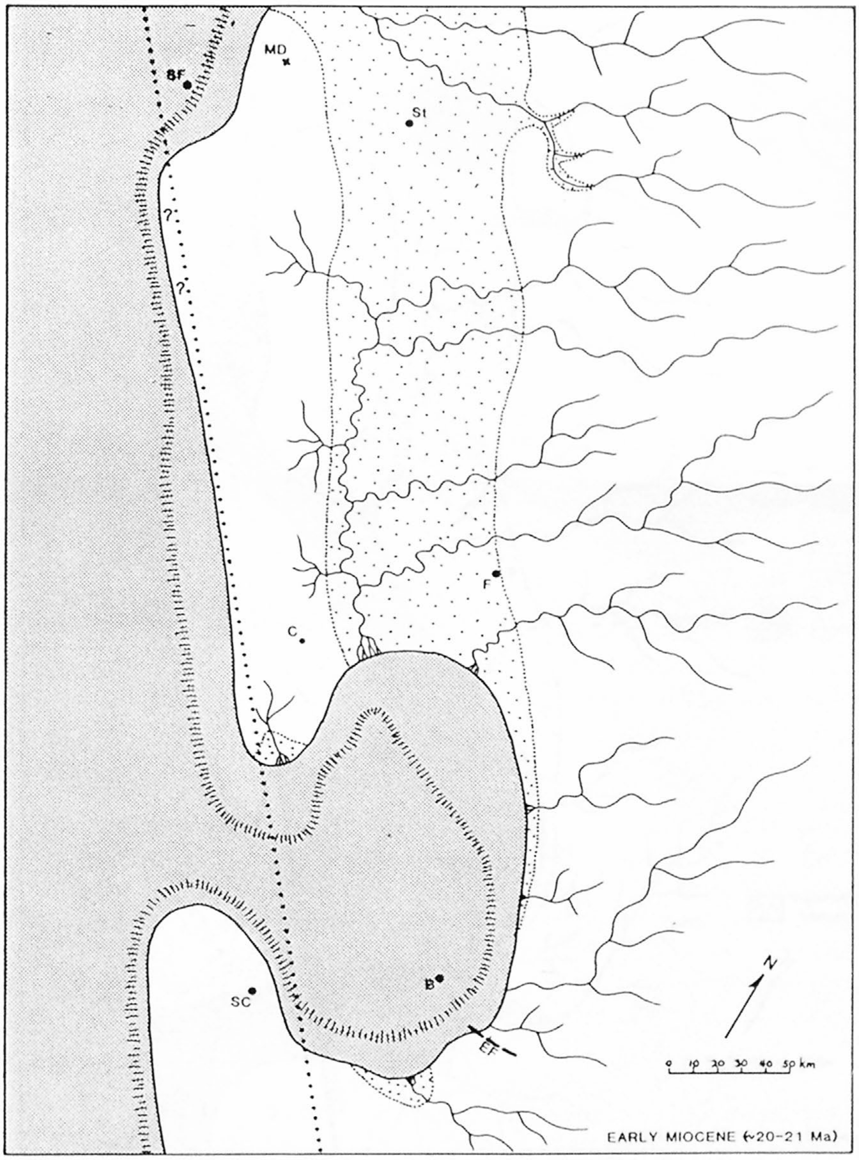

Figure 8.--Early Miocene (about 20-21 Ma) paleogeography of the San Joaquin basin area. EF, Edison fault; SC, Santa Cruz; other symbols as on figure 4. Based on data from Gale and others (1939), Repenning (1960), Addicott (1968), Bandy and Arnal (1969), Graham (1978), Kuespert (1983), Pence (1985) and Stanley (1985).

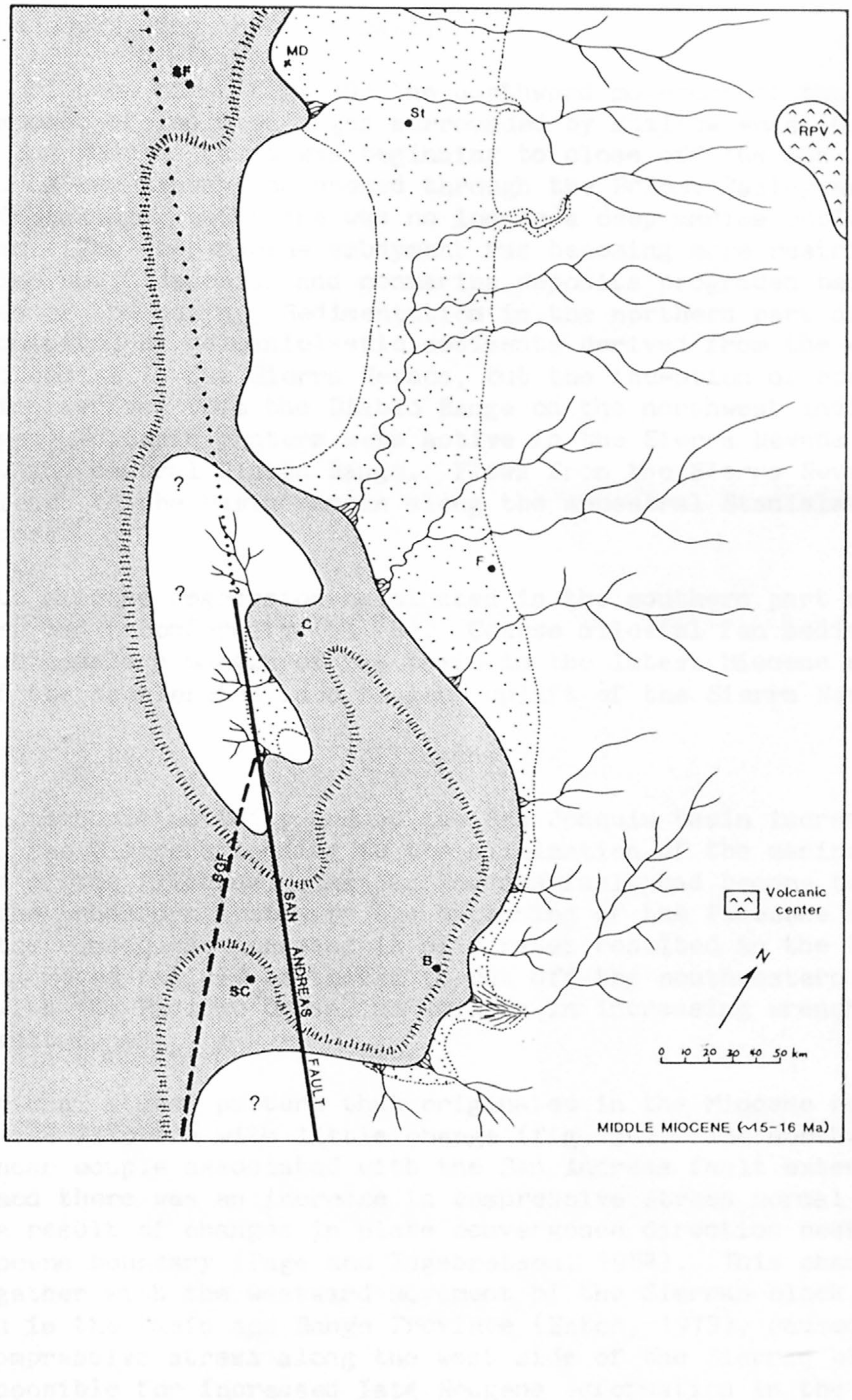

Figure 9.--Middle Miocene (about 15-16 Ma) paleogeography of the San Joaquin basin area. RPV, Relief Peak volcanic center; SC, Santa Cruz; SGF, San Gregorio fault; other symbols as on figure 4. Based on data from Repenning (1960), Addicott (1968), Bandy and Arnal (1969), Fritsche (1977), Graham (1978), Cooley (1982), Kuespert (1983), Bate (1984), Bent (1985), Pence (1985), and Stanley (1985).

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 southern part of the basin, extensive deep-sea fan deposits were derived from the east, the south, and the southwest.

By late Miocene time (fig. 10) 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 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 central Diablo Range. Flows from the Sierra Nevada centers reached at least to the basin margin along the ancestral Stanislaus and San Joaquin Rivers.

The late Miocene regression culminated in the southern part of the basin with a widespread unconformity (pl. 3). Coarse alluvial fan sedimentation along the southeastern 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 in 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 resulted in the Salinia terrane being moved rapidly northward to cut off the southwestern marine connection with the Pacific Ocean, as well as in increasing wrench tectonism along the fault zone.

The regional stress pattern that originated in the Miocene remained in effect into the Pliocene with little change (fig. 3C). 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). 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 is largely responsible for increased late Neogene deformation in the fold belt, including deep-seated thrust faults (Wentworth and Zoback, 1986). 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 is, in turn, probably responsible for the accelerated subsidence of the Maricopa subbasin in the latest Pliocene.

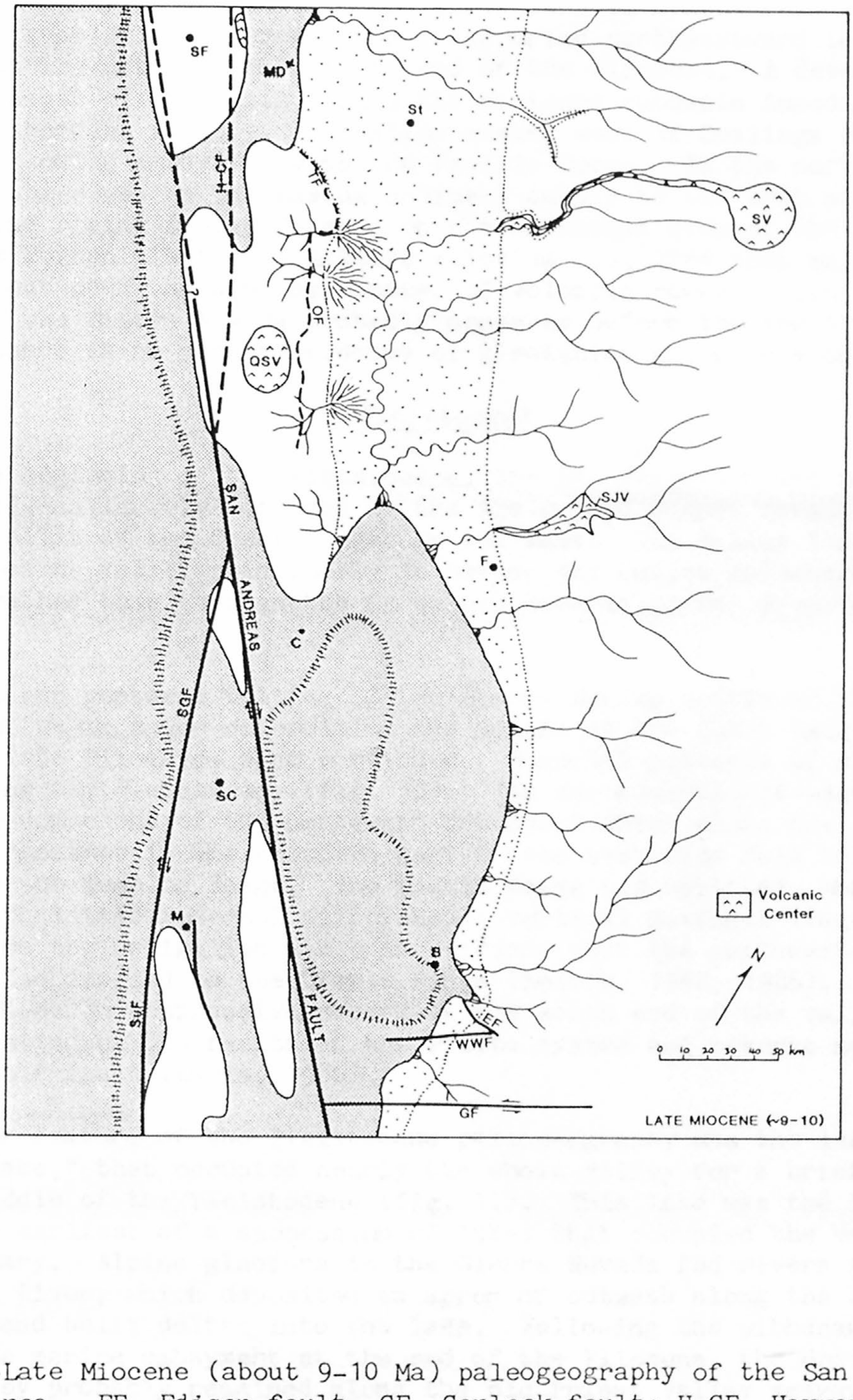

Figure 10.--Late Miocene (about 9-10 Ma) paleogeography of the San Joaquin basin area. EF, Edison fault, GF, Garlock fault; H-CF, Hayward-Calaveras fault; M, Monterey; OF, Ortigalita fault; QSV, Quien Sabe volcanic center; SC, Santa Cruz; SuF, Sur fault; SGF, San Gregorio fault; SFV, San Joaquin volcanic center; SV, Stanislaus volcanic center, TF, Tesla fault; WWF, White Wolf fault; other symbols as on figure 4. Based on data from Repenning (1960), Addicott (1968), Bandy and Arnal (1969), Fritsche (1977), MacPherson (1978), Phillips (1981), and Graham and others (1982).

The paleogeographic map for the Pliocene (fig. 11) differs significantly from the late Miocene map. The embayment is much smaller and the basin, mostly brackish by this time, is enclosed on the south and southwest. Nonmarine deposits prograded into the shallowing embayment from all sides and the now emergent Salinia terrane was transported northwestward to completely close the marine outlet by about the end of the Pliocene. A developing uplift lay to the south of the basin, while the Maricopa subbasin immediately to the north 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. 3D). The north-northeast--south-southwest compressive component of the northwest-southeast shear along the San Andreas fault zone resulted in the southern part of the west-side fold belt being uplifted as the Temblor Range. The Diablo Range was uplifted, more or less 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. 12). 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. Following 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 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. 1) to flow down the now underfit Cholame and Estrella Creeks to join the Salinas River north of Paso Robles.

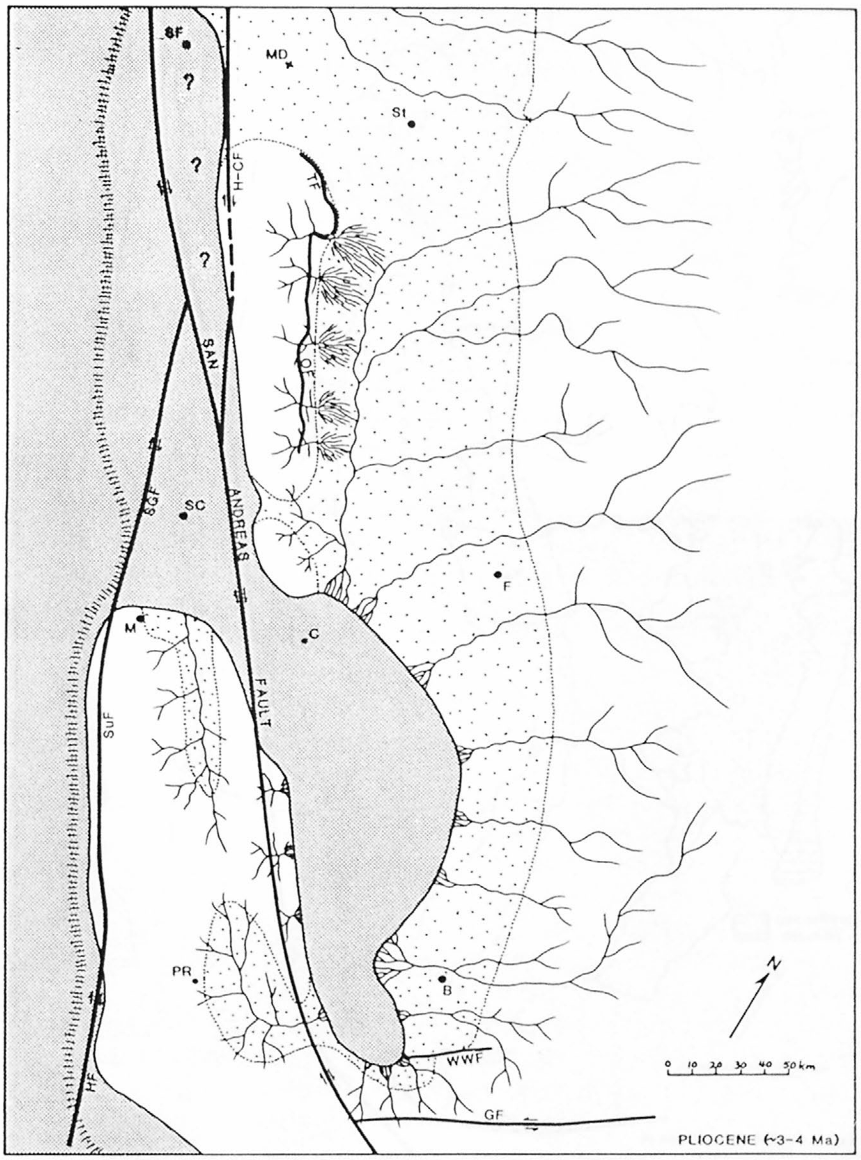

Figure 11.--Pliocene (about 3-4 Ma) paleogeography of the San Joaquin basin area. GF, Garlock fault; H-CF, Hayward-Calaveras fault; HF, Hosgri fault; M, Monterey; OF, Ortigalita fault; PR, Paso Robles, SC, Santa Cruz; SuF, Sur fault; SGF, San Gregorio fault; TF, Tesla fault; WWF, White Wolf fault; other symbols as on figure 4. Based on data from Repenning (1960), Galehouse (1967), Foss (1972), Cole and Armentrout (1979), and Greene and Clark (1979).

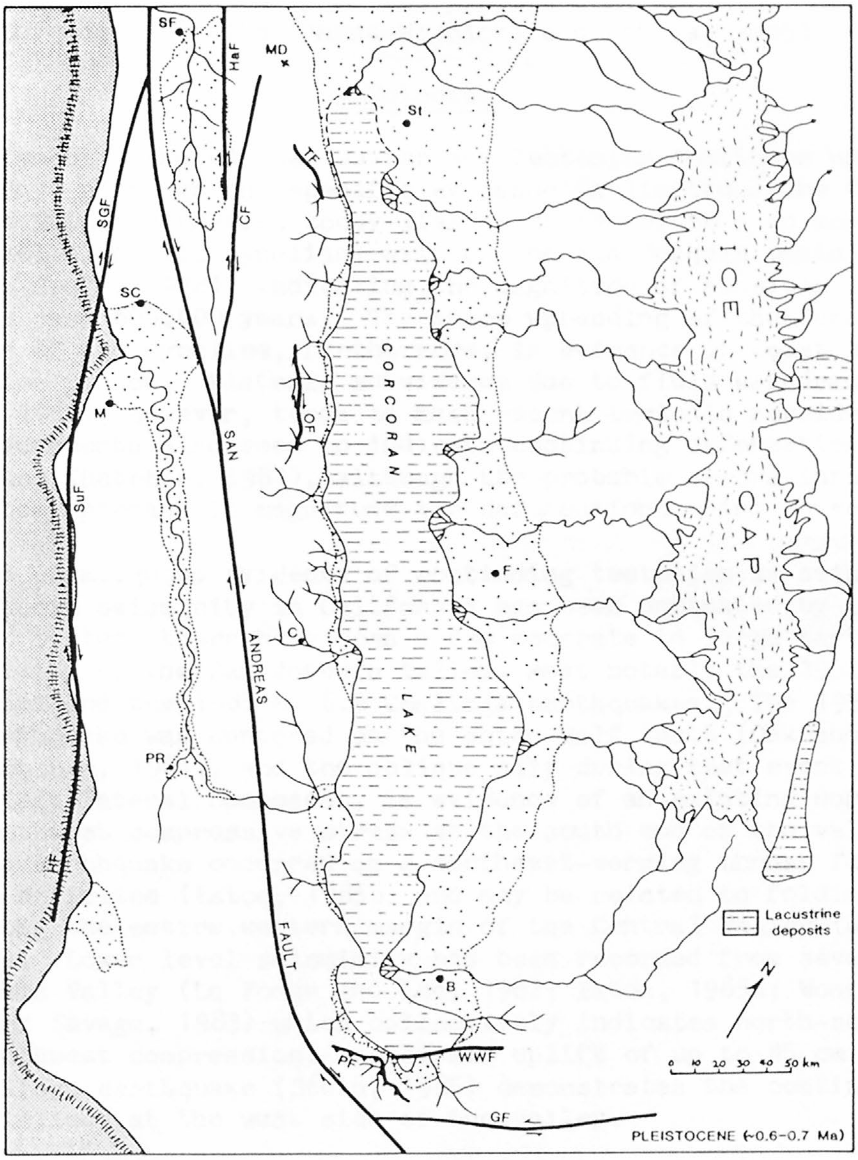

Figure 12.--Pleistocene (about 0.6-0.7 Ma) paleogeography of the San Joaquin Valley area. CF, Calaveras fault; GF, Garlock fault; HaF, Hayward fault; HF, Hosgri fault; M, Monterey; OF, Ortigalita fault; PF, Pleito fault; PR, Paso Robles: SC, Santa Cruz; SuF, Sur fault; SGF, San Gregorio fault; TF, Tesla fault; WWF, White Wolf fault; other symbols as on figure 4. Based on data from Wahrhaftig and Birman (1965), Croft (1972), and Page (1986).

This alternative was chosen for the mid-Pleistocene paleogeography of Figure 15. In any 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 Range uplift during the same period. Historic 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 historic seismicity in California has been dominated by the San Andreas fault system, there have been a few moderate to large earthquakes within the limits of the San Joaquin Valley, most notably the 1952 M_L 7.2 Arvin-Tehachapi and the 1983 M_L 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 western 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) which collectively indicates north-south to northeast-southwest compression. Coseismic uplift of up to 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 causative factor for the regression at the end of the upper Paleocene and lower Eocene depositional sequence, and it was 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 later by wrench tectonism associated with the San Andreas fault system (Dickinson and Snyder, 1979; Page and Engebretson, 1984) and by east-west compression resulting from extension in the Basin and Range Province east of the Sierra Nevada which has induced compressional tectonism along the west side of the basin. The effects of Mendocino triple junction passage were first felt beginning at about 23-24 Ma at the south end of the basin with extension-induced subsidence and volcanism. This was followed at 15-17 Ma by regional uplift in the southern part of the basin that seems to have been associated with passage of the triple junction and may have been related, in some way, to the presence under the basin of the subducted fracture zone (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 high stand 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 17-18 Ma along the Temblor Range segment. Folding continued through the remainder of the Cenozoic and deformation increased in intensity near the San Andreas fault. There is increasing evidence, however, that ongoing deformation at the east edge of the Coast Ranges, and by implication, the basinward expansion of the fold belt, is due to deep-seated eastward-directed thrusting (Wentworth and Zoback, 1986).

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